9th International Conference on

Product Lifecycle Modeling, Simulation and Synthesis

Product Lifecycle Management in Smart, Connected and Sustainable Ecosystem

December 6-8, 2023. Bengaluru

PLMSS 2023 PROCEEDINGS

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PLMSS 2023

9th International Conference on
Product Lifecycle Modeling, Simulation & Synthesis

6th - 8th December 2023 | Bengaluru

Product Lifecycle Management in Smart, Connected and Sustainable Ecosystem

PROCEEDINGS

ORGANISED BY
Aeronautical Development Agency, Bengaluru
In Partnership With SAE INDIA Aerospace Forum
Under The Aegis of PLMSS Trust

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PREFACE

The 9th International Conference on Product Lifecycle Modeling, Simulation & Synthesis (PLMSS 2023) was successfully held at HAL Management Academy, Bangalore, from December 6-8, 2023. Organized by the Aeronautical Development Agency (ADA) in collaboration with the SAEINDIA Aerospace Forum, the conference focused on the theme "Product Lifecycle Management in a Smart, Connected, and Sustainable Ecosystem." It brought together prominent researchers, industry experts, and academicians to delve into the latest advancements in digital transformation, as well as cutting-edge technologies in design, manufacturing, and product sustainment. The event featured a wide array of presentations and discussions, highlighting the rapidly changing landscape of industrial digitalization and its influence on product development processes.

Product Lifecycle Management has undergone a remarkable transformation with the advent of Digital Twin and Digital Thread technologies, fundamentally reshaping how industries approach product development, manufacturing, and maintenance. Digital Twins provide real-time virtual representations of physical assets, enabling advanced monitoring, simulation, and optimization across the product lifecycle, while Digital Thread ensures a seamless flow of data from design to disposal, enhancing decision-making and collaboration. These innovations are particularly groundbreaking in sectors like aerospace, automotive, and heavy manufacturing, driving predictive maintenance, performance optimization, and reduced time-to-market. The conference also showcased a diverse array of presentations, including Artificial Intelligence/Machine Learning applications and immersive solutions like Augmented and Virtual Reality in design and manufacturing.

The conference attracted 133 abstract submissions, of which 104 progressed to full paper submissions. A rigorous peer review process involving more than 80 expert reviewers led to the selection of 65 papers for oral presentation. Of these, 62 authors successfully delivered their presentations. Additionally, 12 papers were selected for the poster session.

On behalf of the conference organisers, we would like to express our gratitude to everyone who contributed to the success of this event and extend thanks to all the authors for their valuable submissions, the reviewers for their meticulous and constructive feedback, and the organizations that participated in the product presentations, enriching the conference with their innovations. We are very much grateful to the sponsors for their generous support and to the members of the conference program committee for their hard work in coordinating and shaping the event. These contributions have been instrumental in realization of the proceedings.

Prof. B. Gurumoorthy
Srinivasa Rao L
Tarun K Chaturvedi
Asutosh Brahma
(Editors)

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TIME	PROGRAM DESCRIPTION		
9:00 AM - 9:30 AM	Registration		
9:30 AM - 11:00 AM	Conference Inauguration		
11:00 AM - 11:30 AM	Tea Break		
11:30 AM - 12:10 PM	KEYNOTE LECTURE 1 **ADVANCEMENTS IN AI AND ITS APPLICATION TO ENGINEERING AND MANUFACTURING** Prof. Asim Tewari Center for Machine Intelligence and Data Science (C-MInDS) Department of Mechanical Engineering, IIT Bombay		
12:10 PM - 12:50 PM	KEYNOTE LECTURE 2 **THE DIGITAL APERTURE – A GLOBAL OPPORTUNITY** Dr. Robert J Rencher Associate Technical Fellow, Boeing Company		
1:10 PM - 2:00 PM	Lunch		
2:00 PM - 2:40 PM	KEYNOTE LECTURE 3 **DFMA - DESIGN FOR MANUFACTURING AND ASSEMBLY "BUILD RIGHT, BUILD FAST "** Shri V S Vasudev Chief Designer (Structural Design), Aircraft Research & Development Center, HAL		
2:40 PM - 3:00 PM	Corporate Track: SIEMENS (Platinum Sponsor) **DIGITAL THREAD – DIGITALLY CONNECTING THE ENTERPRISE** Mr. Gururaj Bengeri Director - Digital Transformation Consulting,SIEMENS		
3:00 PM - 3:40 PM	KEYNOTE LECTURE 4 Shri Sridhar Dharmarajan Executive Vice President & Managing Director, Hexagon Manufacturing Intelligence Division		
3:40 PM - 4:00 PM	Tea Break		
SESSION I	**TRACK 1**	**TRACK 2**	**TRACK 3**
Theme/Time	System Modeling & Simulation	Aircraft Systems - Mechanical	PLM/Applications/ Digital Thread
4:00 PM - 4:30 PM	INVITED TALK – 1 **MBSE–for Sustainable PLM** Mr. Krishna Chaitanya Research Group Head SIEMENS Technology Division	INVITED TALK – 2 **Digital Solutions And Digital Transformations For Aerospace** Megha Navalgund GE, India	INVITED TALK – 3 **Engineering Design Transformation** Ms. Ranjani Rajanikanth Senior Director - Digital Strategy & Transformation Honeywell
4:30 PM - 4:45 PM	CAT-02.6 **Simplifying Parametric Analysis using Variant Modeling.** Arulmani Gnanasekaran and Ruturaj Digraskar Bluekei solutions Pvt. Ltd.	CAT-04.5 **Design, Modelling and Simulation of Deflector Plate for Flow Distribution In Combined Heat Exchanger for A Typical Fighter Aircraft.** Ramana Murthy K V, Sankaraiah Mada and Mahesh Babu S ADA, Bangalore	CAT-09.5 **Enhancing PLM Concepts for Effective Integration of Design andManufacturing in the Development of Composite Airframe** Senthilnathan K, Rajesh Kumar S Sunny Darshan K, Paranthaman N and A Giridharan NAL, Bangalore

PLMSS-2023 Conference Schedule

DAY 1 - 6th DEC 2023

SESSION I	TRACK 1	TRACK 2	TRACK 3
Theme/Time	System Modeling & Simulation	Aircraft Systems - Mechanical	PLM/Applications/ Digital Thread
4:45 PM - 5:00 PM	CAT-02.8 **Graph based Smart Neural Recommendation Mechanism (SNeRM) for system modelling.** Basil Cardoz, Samir Mishra and Ganesh Seshadri Siemens Technology and Services Private Limited, Bangalore		CAT-09.4 **An Efficient Change Management Processes for the enterprises to realize Design Anywhere, Manufacture Anywhere.** Sibichakaravarthy S K and Bala Sabari D Thinkinnov Solution Technologies Private Limited
5:00 PM - 5:15 PM	CAT-02.9 **Numerical Simulation of Test Fixture And Experimental Verification by Full Scale Slosh & Vibration Test of Aircraft External Fuel Tank.** Nisar Ali and Dr Prabha Srinivasan ADA, Bangalore	CAT-04.1 **Environmental Control System flow optimization for fuel tank pressurisation during deck Take-off of single engine jet aircraft** Rahul Agrawal and Sankaraiah Mada ADA, Bangalore	CAT-09.7 **Product Life Cycle Process & Management for Human Spaceflight Missions** Aditya Karan, Gaurav Yadav, Surapaneni Kakati and Gowrishankara CK URSC-ISRO, Bangalore
5:00 PM - 5:15 PM	CAT-02.11 **Enhancing Requirements Engineering: Syntactical Writing and Data Modelling for Improved Aerospace Systems Development.** Tanmay Dube, Suvigya Gupta, Sandesh Puranik and Dhirendra Singh BlueKei Solutions Pvt Ltd	CAT-04.9 **Tool Costing, the unpredictable challenge?** Himanshu Arora, Manoj Tiwari and Rajesh Shankar SIEMENS	CAT-09.6 **Implementation of Process Track Sheet in PLM** Ankush Budihal, Jintu K S, Sumeet Patil, Gokul Krishna and Golla Ramanjulu ADA, Bangalore

PLMSS-2023 Conference Schedule

DAY 2 - 7th DEC 2023

TIME	PROGRAM DESCRIPTION AND VENUE
9:30 AM - 10:10 AM	KEYNOTE LECTURE 5 **SYSTEM ENGINEERING AND DIGITAL TWIN** Dr. Abhay A Pashilkar Director, NAL
10:10 AM - 10:30 AM	Corporate Track:Dassault Systemes (Platinum Sponsor) **VIRTUAL TWIN SOLUTTION EXPERIENCE FOR AEROSPACE & DEFENCE** Mr. Praveen Mysore Technical Director,Dassault Systemes India Pvt Ltd
10:30 AM - 11:10 AM	KEYNOTE LECTURE 6 **COMPLEX AIRBORNE SYSTEM OF SYSTEMS** Dr. K Rajalakshmi Menon, FNAE Distinguished Scientist & Director CABS, DRDO
11:10 AM - 11:30 AM	Tea Break

SESSION II	TRACK 4	TRACK 5	TRACK 6
Theme/Time	Manufacturing, Product Testing & Inspection	Quality - Reliability	New Technologies in Product Development/I 4.0
11:30 AM - 12:00 PM	INVITED TALK – 4 **Ultra-high Temperature Characterization Challenges & Opportunities Aviation Product Lifecycle** Dr P B N Prasad, Dr. A. S. Ahlawat Maapan Lab	INVITED TALK – 5 **Combat Aircraft - Operations & Sustainability** Air Cmde P K Choudhary VSM (Retd)	INVITED TALK – 6 **Autonomous Navigation Of Drones & Its Application In Defence** Dr. Bipin Kumar Tata Elxsi
12:00 PM - 12:15 PM	CAT-05.2 **Prove-out of Jigless Assembly for future Combat Aircraft Programme** Saikat Bhowmik, Balaji H and Srinivasa Rao L ADA, Bangalore	CAT-06.1 **Functional Hazard and Fault Tree Analysis for the Flight Control System of a Transport Aircraft** Ganesh Madhuranath and Achuthan Pankaj	CAT-08.4 **Overcoming Ideation Bottlenecks through Conversational AI** B. Sankar and Dibakar Sen IISC, Bangalore
12:15 PM - 12:30 PM	CAT-05.1 **Comparison of inspection between LASER based scanner and CMM for MBD aircraft structural parts** Sunil Soni, Prem Raj V and Shivakumar B Hosakeri HAL, Bangalore		CAT-08.1 **Opportunities with Generative AI to address challenges of Aviation Industry** Krishnasagar Kulkarni, Venugopal R, Devaraja Holla Vaderahobli and Dr. Ravi Kumar G.V.V Infosys Ltd.
12:30 PM - 12:45 PM	CAT-05.3 **Design And Development of an Airborne Cold Plate Through Vacuum Brazing Technique** Annapurna Sogunuru, Vikram P, Priyank Prasad, Ilavarasu Sivagnanam and Gracy Philips CABS	CAT-06.3 **Development of Novel Techniques for Sensing Propellant Depletion of Low Thrust Engines** Govardhana Reddy Chintala, Mansoor K and Sheethal Antony VSSC	CAT-08.2 **Test-Time Augmentation for Improving the Accuracy of Deep Learning based Defect Inspection Models** Ninad Kulkarni, Apoorv Jain, Aravindh Kalaiyarasan, Srigandhan S.V. and Ujwal Bhate Infosys Ltd.
12:45 PM - 1:00 PM	CAT-05.4 **Generative Design for Additive Manufacturing of Sounding Rocket Crown: A Case Study** Aakash Preetham Vadlakunta, V S Sooraj, V Anil Kumar, Apurba Roy, V Aravind and G Ayyappan IIST	CAT-06.4 **Implementation of Quality Management System through PLM framework** Vijaya Kumar Shanmugam, Kannagi Ad, Srinivasan G, Palanivel G and Balamurugan V DRDO	CAT-08.3 **Integration of Blockchain Technology with PLM** Gokul Krishna, Ankush Budihal and Golla Ramanjulu ADA, Bangalore
1:00 PM - 1:45 PM	Lunch		

SESSION III	TRACK 7	TRACK 8	TRACK 9
Theme/Time	Product Design - CAD /MBD	System Modeling & Simulation	Product Operations, Support and Sustenance
1:45 PM - 2:15 PM	INVITED TALK – 7 **The PIm Perspective For The Next Generation Combat Aircraft Programme** Mr. Krishna Rajendra Neeli Offg. Project Director (Advanced Medium Combat Aircraft) ADA	INVITED TALK – 8 **Virtual Verification & Validation – Impact of Simulation on Safety, Efficiency and Innovation** Mr. Raphael Van der Vorst Systems Engineering Technical Consultant SIEMENS	INVITED TALK – 9 **Digital Twin Framework For Health Management Of Aircraft Systems In Product Lifecycle** Dr V Sudhakar Group Director (HUMS) ADA
2:15 PM - 2:30 PM	CAT-01.5 **Model Based Definition (MBD) implementation in PLM Framework for development of Combat Aircraft** Illuru Aravinda Kumar, Hari Soni, K. Karthiga, Tarun K Chaturvedi and V. Vani ADA, Bangalore	CAT-02.2 **Implementation of an MPC-based Closed Loop Trajectory Planning and Trajectory Tracking Approach in a Discrete Virtual Environment** Shantanu Shukla, Varun Katre, Balasubramanian Subramani Sellamani, Rajvardhan Pattanashetti, Natarajasundaram and Rajasekhar Roopavatharam IIT, Bombay	CAT-11.4 **Development of a Data Analysis Tool for Flight Strain Predictions** Veluri S Chinmayi, Srinivas Vankudothu, Ankur Agrawal, Thamotharan T and Sudhakar V PES University, Bengaluru
2:30 PM - 2:45 PM	CAT-01.1 **Implementation of Model Based Definition for a Fighter Aircraft** Kiran Nellore, Dr. Prashanth A N, Prem Raj V, and Vasudev VS HAL, Bengaluru	CAT-02.3 **Vibration Analysis of Aircraft Pipelines to Generate Inputs for Clearance Checks in DMU** Hemalatha E, Gourav Dutta and Mohamed Nishad ADA, Bengaluru	CAT-11.2 **Availability enhancement of aircraft using Deep Learning techniques for unscheduled maintenance** Antony GratusVaruvel, Akhrsh J Pillai, Rammohan V Khaki and Dr Rajendra Prasath R ADA, Bengaluru
2:45 PM - 3:00 PM	CAT-01.4 **Computer-Aided Assembly Sequence Generation for a Hierarchical Product Structure of Aircraft Assemblies** Aniruddha Rajendra Magdum, Ravi Prasad S, Sai Kishore K and Dr. R. K. Satpathy DIAT, Pune	CAT-02.4 **Effective Model-Based Systems Engineering Framework for Logic Intensive Applications: Digital Anti-skid Brake Management System Case Study** Manju Nanda, Ganesh Madhurnath, Shrilatha Acharya, Shamsundar Dhage, Alexander Kale, Viswanathan S, Neelakanta E and G. K. Singh NAL, Bengaluru	CAT-11.1 **Technical Publications for Indigenous Fighter Aircraft Programme – An SLM Driven Approach** Murali Krishna Teki, Krishna Bhat and Satish Kumar ADA, Bengaluru
3:00 PM - 3:15 PM	CAT-01.3 **Increasing Efficiency of Aircraft Ground Handling Operations** Indira Narayanaswamy and Ajith CB	CAT-02.7 **Assessment of Bird Impact and Foreign Object Damage on Infrared Search & Track System and Airframe of Modern Combat Aircraft** Anil Kumar Gupta and Prabha Srinivasan ADA, Bengaluru	CAT-11.3 **Time Series Data Compression Using Piecewise Linear Model For IVHM Applications** Srinivas Vankudothu and Sudhakar Veluri ADA, Bengaluru

SESSION III	TRACK 7	TRACK 8	TRACK 9
Theme/Time	Product Design - CAD /MBD	System Modeling & Simulation	Product Operations, Support and Sustenance
3:15 PM - 3:30 PM	CAT-01.2 **Optimization of INS/GPS Harmonization on LCA Mk1 aircraft** Md Madar Khan and Gurusewak Singh ADA, Bengaluru	CAT-02.13 **Full scale fatigue testing of a fighter aircraft by Flight-by-flight methodology** Agam Sharan and Deepa James ADA, Bengaluru	CAT-11.5 **Digital Framework for Indigenous Fighter Aircraft Development & Sustenance** Krishna Bhat, Murali Krishna Teki and Satish Kumar ADA, Bengaluru
3:30 PM - 3:48 PM	Tea Break		
3:48 PM to 4:00 PM	Corporate Track – ANSYS (DiamondSponsor)		
4:00 PM – 5:30 PM	Panel Discussion – Advanced Manufacturing for Defence Mr K Ravi HAL LCA-TD, Mr Laxmesh L&T, Mr Sudhir Kamath MTRDC, Dr Ravishankar NAL & Mr. Anil K Sogi, GM (EW&A), BEL		

PLMSS-2023 Conference Schedule
DAY 3 - 8th DEC 2023

TIME	PROGRAM DESCRIPTION AND VENUE
9:30 AM - 10:10 AM	KEYNOTE LECTURE 7 **DIGITAL ENABLEMENT OF THE DESIGN, BUILD & MAINTENANCE OF A SUSTAINABLE INDIGENOUS AIRCRAFT PROGRAM** Mr. Peter Bilello President & CEO, CIMdata
10:10 AM - 10:25 AM	Corporate Track – CADOPT Technologies Pvt Ltd (Diamond Sponsor) **EMERGING PLM TRENDS FOR THE A & D DIGITAL THREAD CONTINUUM** Ms Renuka Kamath Principal Solutions Consultant, PTC
10:25 AM - 11:05 AM	KEYNOTE LECTURE 8 **DIGITAL SOLUTIONS FOR AEROSPACE INDUSTRY** Mr. Kamlesh Kumar Gupta Head – Technical Services & Skill Development - Tata Advanced Systems Ltd
11:05 AM - 11:30 AM	Tea Break

SESSION IV	TRACK 10	TRACK 11	TRACK 12
Theme/Time	Aircraft Systems - Mechanical	Product Visualisation	Digital Twin
11:30 AM - 12:00PM	INVITED TALK – 10 **PLM For Aircraft Critical Systems Qualification & Certification** Mr. Shyam Karigiri Managing Director Moog India Technology Center	INVITED TALK – 11 **A Human Factor Analysis of Metaverse And Case Studies On Manufacturing** Prof. Pradipta Biswas Professor (CPDM), IISc	INVITED TALK – 12 **Operationalizing AI/ML in Aerospace & Defense Applications** Dr. Badarinath Ambati and Sandeep Yadav Altair, India

SESSION IV	TRACK 10	TRACK 11	TRACK 12
Theme/Time	Aircraft Systems - Mechanical	Product Visualisation	Digital Twin
12:00 PM - 12:15 PM	CAT-04.4 **Effect of Residual stress on creep behavior for IN718 Superalloy of TIG welded joints** Kaustav Barat, Nikhil Kumar C, Vijay Petley,Pradeep Kumar A and KarodiVenkateswarlu NAL, Bengaluru	CAT-07.3 **Augmented Reality based Mobile App in Aircraft Applications** MaharudraKharsade and Pradipta Biswas IISC, Bengaluru	CAT-10.3 **Prediction of Remaining Useful Life of Amagb Gearbox Based on Digital Twin Concept** Bharathi D, Chandrasekar KG, Vijaya Kumar S, Srinivasan G, Solai Raju M and Balamurugan V CVRDE, DRDO
12:15 PM - 12:30 PM	CAT-04.6 **Development of eco-friendly Zn-Ni plating on Low alloy high strength steel parts, as an alternative to Cadmium plating, for aircraft applications.** Ashish Narkale, Dr. R K Rayudu, Dr. Angappan M, Teslin Johnson, Meenu Srivastava, Sai Venkata Pramod Kumar ADA, Bengaluru	CAT-07.4 **AR application for Real-Time Aircraft Parts Identification and Labelling and Associated Information** Amardeep R M, Vinothkumar S, Akshat Jain and S Ravi Parasad ADA, Bengaluru	CAT-10.2 **Virtual Twin Transformation** Olivier Mougin, Yuvaraj Murali, Manickam Damodharan, Balasubramanian N, Rajasekhar R and Thomas Lorentz, Renault Nissan Technology and Business Center private limited
12:30 PM - 12:45 PM	CAT-04.2 **Experimental Study on Enhancement in the Tribological Behavior of Low Carbon Steel with Military (MIL) grade Lubricant using MoS2 Nano Additives for Aerospace Applications** Senthil Kumar Munisamy, Elayaperumal A, Vidhya Sagar SS and SankaraiahMada ADA, Bengaluru	CAT-07.2 **Digital Mock-Up Analysis inclusive of displacements in dynamic environment of Fighter Aircraft** Anjan Murmu, Mithil Kumar S, Gokul V K, Jaya Prakash Narayana Aila and Srinivasa Rao L ADA, Bengaluru	CAT-10.4 **Virtual Fatigue Testing of a fighter aircraft using a Fatigue Digital Twin: A framework and challenges** Ravinu Garg and Deepa James ADA, Bengaluru
12:45 PM - 1:00 PM	CAT-04.8 **Optimization of Composite Material For Cargo Bike Frame** P B Keerthanna, Waddinkatti Afsar and G Muralidhar Altair India Private Limited	CAT-07.1 **War Gaming Scenario Generation for Training and System Evaluation** Sukhen Saha, Supriya Kumbharey, Antim Maida, S K Sahoo and M Backialakshmi CABS-DRDO	CAT-10.5 **Duty cycle based digital twin approach to calculate remaining useful life of an aircraft gearbox.** Amol Korde Hexagon Manufacturing Intelligence
1:00 PM - 1:15 PM	CAT-04.7 **High-Pressure Water Separation System Coupled with Aircraft Fuel in Environmental Control System for Typical Aircraft Application** Vinay Pratap Singh Negi and Chennu Ranganayakulu BITS-Pilani,Rajasthan	Special INVITED TALK **VIRTUAL REALITY FOR AIRCRAFT DESIGN** Ms. P Archana Hebbar Senior Principal Scientist NAL, Bengaluru	CAT-10.1 **Demystifying Digital Twins: An example of EV battery twins to describe technologies and use cases** Nikhil Joshi and Girish Sohoni Hexagon Manufacturing HCL Technologies Limited
1:15 PM - 2:00 PM	Lunch		

SESSION V	TRACK 13	TRACK 14	TRACK 15
Theme/Time	System Modeling & Simulation	Aircraft Systems - Avionics / Electrical	PLM/Applications/ Digital Thread
2:00 PM - 2:30 PM	INVITED TALK – 13 **Model Based System Engineering** Vishal Naik Bolnekar Ansys	INVITED TALK – 14 Manjula / Karthikeyan BEL	INVITED TALK – 15 **GENAI Led Digital Transformation Across Aircraft Lifecycle** Dr. Ravi Kumar G. V. V. VP & Head Advanced Engineering Group, Infosys (DS)
2:30 PM - 2:45 PM	CAT-02.5 **Enhancing Efficiency and Standardization in CAE driven Automotive Product Development through Template-based Automation for Load Case Setup and Report Generation** Hareesh Narayanaswamy and Jojy Johnson Altair Engineering		CAT-09.3 **PLM for Achieving Connected Products and Sustainability** Vivek Chaturvedi and Rakesh Kumar MOOG India Technology Center
2:45 PM - 3:00 PM	CAT-02.1 **Towards Seamless Collaboration in Aerospace Analysis: The SMARaN System Implementation** Baburaj A and Mahadeshkumar A ADA, Bengaluru	CAT-03.3 **A Test Bed for Design & Testing of Multi Sensor Data Fusion** B R Kapuriya, A Muthukumar, Nagaraju B and Rajesh R DRDO	CAT-09.1 **Configuration and Customization of a PLM Software for the Computer-Aided Design (CAD) Data Management** Anand Singh, Narayana R and Mahantesh SP NAL, Bengaluru
3:00 PM - 3:15 PM	CAT-02.10 **Configuration and Customization of a PLM Software for the Computer-Aided Engineering (CAE) Simulation Data Management** Anand Singh, Narayana R and Mahantesh SP NAL, Bengaluru	CAT-03.1 **A Control System design approach for Continuous Mixer and Extruder** Raghu Kodi, Vijay Kumar Nidagalkar and Ananthapadmanabha K M CMTI	CAT-09.2 **Reimagining product structure for Modular Build of a Fighter Aircraft** Prem Raj V, Vijayaragavan S and Vasudev VS HAL, Bengaluru
3:15 PM - 3:30 PM	CAT-02.12 **Structural Analysis of a Ship Using Simcenter FEMAP with NX Nastran** Jerry Clifford Francis and Pramod S	CAT-03.2 **Investigation of Electric field Distribution on a Single phase HV Cables using Finite Element Modelling** Mahesh Balakrishna Varrier and Stuart Steadman	CAT-09.8 **Driving Engineering and Manufacturing Efficiencies Through Digital Thread** Sunil Sidhanty and Neeraj Garg Infosys Ltd
3:30 PM - 4:00 PM	**Poster Presentations**	**Poster Presentations**	**Poster Presentations**
4:00 PM - 4:30 PM	Closing Ceremony followed by High Tea		

All common session will be held at the auditorium
Hall details for the parallel sessions will be announced

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Published Papers

CAT-01 Product Design - CAD /MBD			
Authors	**Title**	**Paper No.**	**Page No.**
Prem Raj V, Kiran Nellore and Vasudev V S	Implementation of Model Based Definition for a Fighter Aircraft	CAT-01.1	38
Md Madar Khan and Gurusewak Singh	Optimization of INS/GPS Harmonization on LCA Mk1aircraft	CAT-01.2	50
Indira Narayanaswamy and Ajith C B	Increasing Efficiency of Aircraft Ground Handling Operations	CAT-01.3	54
Aniruddha Rajendra Magdum, R. K. Satpathy, Ravi Prasad S and Sai Kishore K	Computer-Aided Assembly Sequence Generation for a Hierarchical Product Structure of Aircraft Assemblies	CAT-01.4	60
Illuru Aravinda Kumar, Hari Soni, K. Karthiga, Tarun K Chaturvedi and V. Vani	Model Based Definition (MBD) Implementation in PLM Framework for Development of Combat Aircraft	CAT-01.5	72

Published Papers

CAT-02
System Modeling, Simulation, MBSE, CAE & Analysis

Authors	Title	Paper No.	Page No.
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Implementation of MBD for a Fighter Aircraft

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Abstract - Model Based definition(MBD) is the process of incorporating 3D digital data(models) such as 3D dimensions and tolerances, to provide a technical definition of individual components and product assemblies within 3D CAD model. MBD is the method of providing the ONE reference source:a 3D cad model with PMI (Product manufacturing Information), GD&T(Geometric Dimensioning and Tolerancing) symbology and annotations. In this paper, a complete framework of implementation of Model Based Definition for a fighter aircraft is presented. The implementation also covers customization and finalization of lightweight downstream deliverables for Sheet metal and machined parts in PLM environment. Addressing the infrastructure requirements on both the design side as well as down stream side and the methodology of change management in MBD for PDM environment is presented.

Keywords - Model Based Definition (MBD), Geometric Dimensioning and Tolerancing (GD&T),Product Data Management System (PDM) ,Product Life cycle management (PLM),Product manufacturing Information (PMI).

I. INTRODUCTION

The design and development of fighter aircraft demands a robust life cycle management approach that ensures precision, collaboration, and adaptability throughout the entire product life-cycle. In Prototype Phase,the need for faster design iterations with multiple configuration changes in each iteration is required to achieve an optimized product meeting stringent performance requirements. During Preproduction and Production phases only a few design changes are required where as in the post production and service phases, the absorption of retrospective changes in design due to upgradation as per customer requirements, technical life enhancements etc lead to changes in design data and consequent changes downstream data .To provide these requirements traditionally design divisions of companies relied heavily on 2D drawings as a master source for conveying critical design information, resulting in potential communication gaps and expensive errors during the manufacturing and assembly stages in the above mentioned phases. 2D drawings presented several challenges that could impact the efficiency and accuracy of the design and manufacturing process that include ambiguity in interpretation, Error-Prone data Transfer from 3D model to 2D drawings, limited visualization ,non value adding and time consuming conversion of data from 3Dmodels to 2D Drawings. Also in this era of digital transformation, dependence on 2D drawings can hinder the integration of new technologies and tools for design optimization, simulation, and analysis.

In the recent past, advancements in computer-aided design (CAD) have significantly influenced aircraft design processes, enabling engineers to create sophisticated digital models that mimic real-world aircraft configurations. To address these challenges and usher in a new era of design, the aerospace industry is increasingly adopting Model-Based Definition (MBD) as a transformative approach. MBD represents a fundamental departure from the conventional 2D drawings, by encompassing a 3D comprehensive digital model as an authoritative single source of information for all the product information that consists of a 3D solid model with all geometry features as well as 3D annotations of required tolerances and manufacturing instructions, to specify a complete product definition , including geometric dimensions, tolerances & annotations, and other relevant engineering data .

With MBD, most of the data related to a product are structured inside native CAD models, instead of being scattered in different forms through the PLM database[1]. MBD as an integral part of product life cycle management offers a digital, model-centric approach that streamlines product information exchange, enhances collaboration, reduces errors, and accelerates decision-making across the product life cycle leading to a Model-Based Enterprise (MBE) . A Model-Based Enterprise uses MBD to define the product requirements and specifications instead of the paper-based document as the data source for all engineering activities throughout the product life cycle. In MBE, models are used to drive all aspects of the product life cycle, and this data is created once and reused for all downstream activities [2].

In this context this research paper aims to explain the implementation of MBD for a fighter aircraft with examples of Machined, Sheetmetal and Composite components and assemblies along with concepts integrated into MBD such as GD&T and DFMA.The Paper also gives overview of holistic integration of MBD with customized PDM, Usable Formats for lightweight downstream deliverables, infrastructure considerations and change management in MBD environment. Challenges and limitations in the successful implementation of MBD, including technical barriers, organizational resistance, and interoperability concerns between various software systems are explained. Through examination of these interrelated aspects, this study seeks to provide insights into the benefits, challenges, and opportunities arising from the convergence of these methodologies in Implementation of MBD, offering a blueprint for enhanced efficiency and productivity.

II.ANALYSIS

2.1 THE NEED FOR MBD

In aerospace design, the 2D drawing is the primary way to convey a product's geometry, design intent and other related information for manufacturing & assembly throughout its lifecycle. Using 2D drawings can lead to problems such as difficulty in imagination for manufacturer and inspector, misinterpretation by users. In creation of drawings during design phase, non value added and cumbersome duplication is involved in conversion of 3D CAD models to 2D giving scope to human errors during data conversion. These Interpretation errors, duplication errors or revision inconsistencies can contribute to costly mistakes that quickly translate into lower quality and productivity. According to a research conducted by Siemens Digital Industries Software, the use of 2D drawings to communicate downstream production requirements adds an unnecessary burden to the product development cycle.[3]

In an internal study conducted for the prototype of a fighter aircraft, the following results were obtained which conveyed that Model-Drawing discrepancy errors were a major portion of the Production queries received from the Manufacturing engineering department to Design department. The results declare the need for a better system for conveying design data without redundancy.

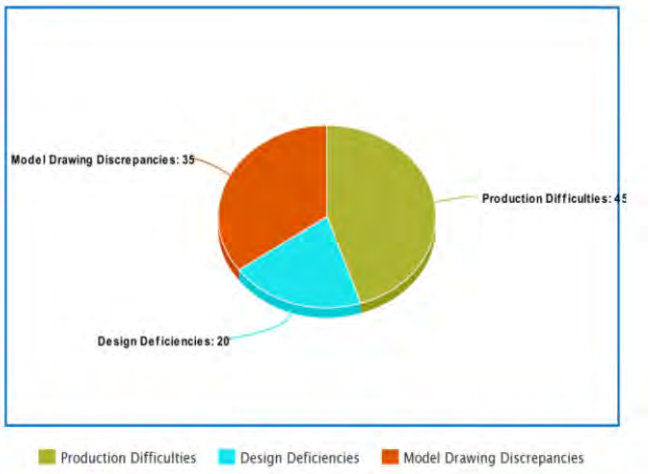

Fig. 1. Model drawing Discrepancies in Production Queries

In a research conducted by Purdue University College of Engineering it is proven that 3D models are less ambiguous than 2D drawings and removes drawing-to-model discrepancy.

Model-Based Definition (MBD) is a strategy to shift from paper-based 2D drawings to 3D CAD models incorporating all the product related information so that 2D drawings are no more needed [4] .Also, With MBD, product teams can capture and share engineering requirements within the 3D model, thereby permitting full use of the design intent. Through the use of MBD the time and cost of documenting a part can be reduced, make early involvement of manufacturing easier, Limit redundant annotation and views – normally created on drawings in an attempt to clarify part design requirements – leads to better communications with fewer interruption errors, improved first time quality and increased productivity.

2.2 REASONS TO IMPLEMENT MBD

1. Significant design hours saved compared to drawing centric approach.
2. Engineering time is saved which can be utilized for design and product development activities.
3. Reduces human error through typing or interpretation.
4. Machine-readable 3D CAD and PMI for automation.
5. More feature-rich data for better instructions for the end user.
6. Higher quality inspections with measurement optimization algorithms.
7. Overcomes breakdowns in associativity between models & drawings and the difficulty of view updates
8. Shorter product development cycles, faster delivery to customer.

2.3 MBD IMPLEMENTATION PLAN

Implementing Model-Based Definition requires a systematic approach to ensure a successful transition from traditional 2D drawings to a 3D model-centric approach.

In developing methodology for MBD implementation to enhance PLM, the following factors are considered:

a. Integration with PLM Strategies: Aligning MBD adoption with existing PLM strategies facilitates a seamless transition and utilization of resources optimally.
b. Standards and Interoperability: Collaborating with industry stakeholders to establish common MBD standards and ensure software interoperability.
c. Training and Skill Development: Providing comprehensive training to engineers and professionals to foster skill development.
d. Data Management and Security: Implementing robust data management and security protocols to safeguard digital product data.

The framework adopted for MBD implementation is outlined in Fig .2 and discussed here :

2.3.1 Define MBD Project scope and Objectives:

Outline the scope of MBD implementation and Clearly define the objectives you want to achieve with MBD implementation. These may include reducing drawing related errors reduced design cycle times, improved accuracy, cost savings, and enhanced collaboration between different stakeholders .

Create a step-by-step roadmap for the implementation process and identify the critical components that will be the focus of the transition to MBD. Break down the implementation into manageable phases, considering factors like complexity, available resources, and potential impacts on existing operations.

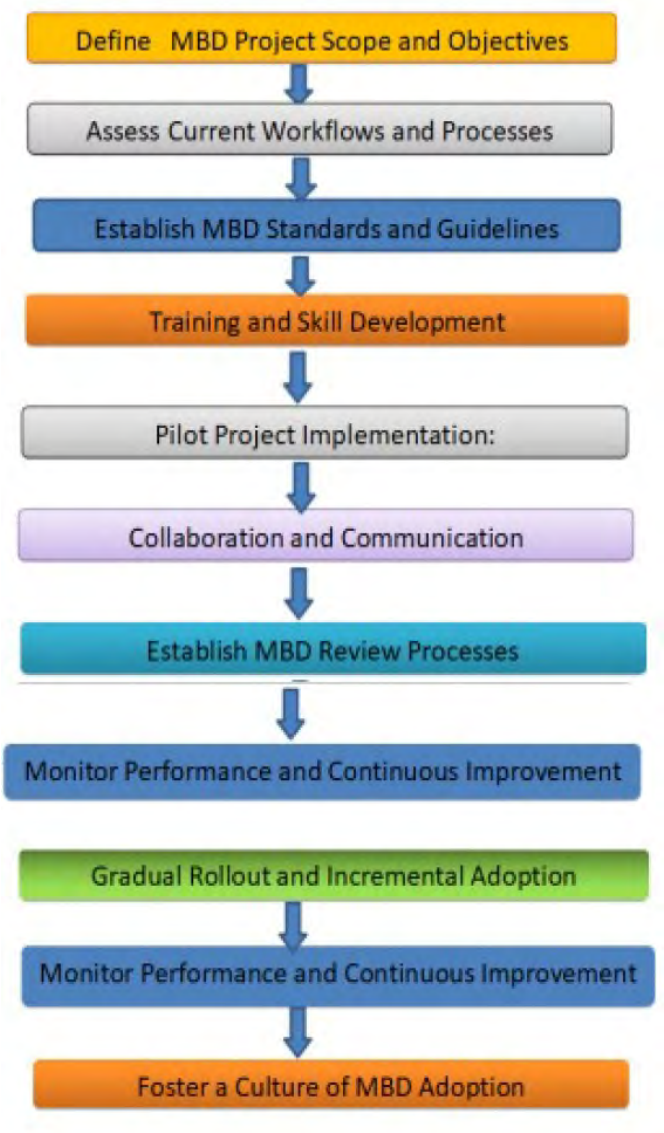

Fig 2 .Steps in implementation of MBD

2.3.2 Assess current workflows and processes:
Conduct a thorough analysis of the existing product development and PLM processes. Thorough evaluation of the existing workflows and processes related to design, manufacturing, inspection, and collaboration. Identification of pain points, challenges, and inefficiencies associated with 2D drawings. This assessment helps in understanding the areas where MBD can provide the most significant improvements. Identify the areas where MBD can provide the most significant benefits, such as reducing errors, improving communication, and streamlining manufacturing and inspection.

2.3.3 Establish MBD standards and guidelines:
Develop comprehensive MBD standards and guidelines that outline the required data format, modeling practices, annotation conventions, and GD&T usage. These standards ensure consistency and uniformity across the organization and facilitate interoperability between different teams and stakeholders.

Identify the relevant industry standards and regulations that govern MBD and PLM in aerospace. Choose the appropriate software and tools for creating, managing, and sharing MBD data. Consider compatibility with existing CAD/CAM/CAE systems and the ability to integrate with the PLM system.

Define Product Information - Clearly define all the necessary product information directly within the 3D model. This includes dimensions, tolerances, surface finishes, material specifications, GD&T (Geometric Dimensioning and Tolerancing), assembly instructions, and any other relevant details.

Define Model Structure- Establish a clear and consistent model structure. Organize the model's features, annotations, and metadata to facilitate effective communication of product information.

Implement GD&T Standards - Adopt GD&T standards (such as ASME Y14.41 Digital Product Definition Data Practices or ISO 16792 Technical Product Documentation– Digital Product Definition Data Practices) to communicate precise engineering tolerances and specifications within the 3D model.

Standardize Model Formats - Choose a standard format for 3D models that supports MBD. The most common format used for MBD is ISO 10303 (STEP). Ensure all stakeholders can access, read, and work with this format. Selection of Suitable MBD Software and Tools-Appropriate MBD software and tools to be chosen that align with the organization's needs and capabilities. Factors such as compatibility with existing PLM systems, ease of use, and support for industry standards like ASME Y14.41 or ISO 16792 for MBD to be considered.

Quality Control and Validation- Establish procedures for quality control and validation of the MBD data. Ensure that the 3D models, annotations, and metadata adhere to the specified standards and accurately represent the product requirements.

Data Management and Security- Implement a robust data management system to store, share, and secure the MBD data throughout the product lifecycle.

Compliance and Regulations-Ensure that the MBD implementation complies with relevant industry regulations and standards. Keep track of updates and changes to these standards.

Integrate MBD data into the PLM system -Ensure that it becomes an integral part of the product's lifecycle management. This integration will facilitate data exchange and version control, ensuring everyone works with the latest information.

Document MBD Standards and Guidelines- Create a comprehensive documentation repository that includes MBD standards, guidelines, best practices, and templates to ensure consistency across projects.

2.3.4 Training and Skill development:
The relevant teams and individuals including design engineers, manufacturing teams, quality control, and suppliers to be trained on MBD concepts, tools, and best practices. Skill development is essential to ensure that the workforce can effectively utilize the selected MBD software and understand the new modeling and annotation techniques. Ensure they understand the changes in processes and their roles in the new workflow.

2.3.5 Pilot Project implementation:
Start with a small-scale pilot project to test the MBD implementation in a controlled environment. Select a relatively straightforward component or sub assembly that will allow for a smooth transition. T. Assess the results,gather feedback from the involved teams, and use the insights to fine-tune the MBD implementation process. This will help identify potential challenges and validate the effectiveness of the chosen approach.

2.3.6 Collaboration and communication:
Foster a culture of collaboration and effective communication among different teams involved in the product lifecycle. viz, between design, manufacturing, and quality assurance teams to drive successful MBD adoption.Encourage collaboration and communication between design, engineering, manufacturing, and inspection teams throughout the MBD implementation process.

Regularly conduct meetings and workshops to address concerns, share best practices, and ensure that everyone is aligned with the MBD objectives. Engage with suppliers and ensure they can work with MBD data. Collaboration with suppliers using MBD can improve supply chain efficiency and reduce errors.

MBD enables seamless sharing of information, but it requires clear communication channels and protocols.

Integrate MBD data into the PLM system to ensure that it becomes an integral part of the product's lifecycle management. This integration will facilitate data exchange and version control, ensuring everyone works with the latest information .Work closely with suppliers to ensure they can interpret and work with the MBD data effectively and provide training and support as needed.

2.3.7 Establish MBD review Processes:

Define key performance indicators (KPIs) to measure the success of the MBD implementation. These Performance Metrics may include reduced lead times, improved design accuracy, cost savings, and enhanced collaboration.

2.3.8 Gradual rollout and Incremental Adoption:
Gradually scale up the MBD implementation across the entire project, considering the lessons learned from the pilot project and early stages of implementation. Gradually roll out MBD to other aerostructure projects ensuring that the lessons learned from the project are applied to subsequent implementations.

2.3.9 Monitor Performance and continuous improvement:
Regularly monitor the effectiveness of MBD implementation and evaluate its impact on product development, manufacturing efficiency, and overall collaboration.

Gather feedback from stakeholders regularly and use this feedback to refine and improve the MBD implementation continuously.

2.3.10 Foster a culture of MBD adoption:
Document the entire MBD implementation process, including challenges faced and solutions implemented. Use this documentation for future training and reference purposes.

By following the mentioned methodology, MBD can be effectively implemented in organizations leading to improved efficiency, accuracy, and collaboration across the entire product life cycle.The timeline for MBD implementation can vary depending on factors such as organizational size, complexity of products, and existing PLM maturity. Initial phases involve pilot projects to assess feasibility and benefits, followed by phased integration across product lines.

2.4 CONCEPTS IMPLEMENTED WITH MBD
2.4.1 Geometric Dimensioning and Tolerancing (GD&T)
MBD gives scope for applying GD&T symbols in 3D model itself with part features as Datums including the allowable variation in geometric features, such as dimensions, tolerances, form, and orientation . This ensures that manufacturing and inspection processes adhere to the required specifications as per design intent.

PMI in MBD encompasses all annotations, GD&T, and metadata embedded within the 3D model. It communicates design intent, manufacturing requirements, and inspection guidelines, making it an essential component of MBD.GD&T symbols are used in the 3D model to define the allowable variation in geometric features, such as dimensions, tolerances, form, and orientation. This ensures that manufacturing and inspection processes adhere to the required specifications. Precise Geometric Specifications: GD&T allows designers to precisely define the form, orientation, location, and size of features on the 3D model. Interoperability and Standards Compliance: GD&T follows established standards (e.g., ASME Y14.5) that provide a consistent and standardized way of defining tolerances. This promotes interoperability among different stakeholders and ensures compliance with industry practices. Automated Inspection and Quality Control: GD&T in MBD allows for automated inspection using Coordinate Measuring Machines (CMMs),3D Hand scanners and other inspection tools. The 3D model provides all necessary information for inspections, leading to faster and more accurate quality control processes. Design Intent Preservation: By using GD&T in MBD, the design intent is better preserved throughout the product lifecycle. This ensures that the end product remains true to the original design specifications, even as changes occur during the development process.

Improved Communication and Collaboration: GD&T provides a common language for communicating design requirements between designers, engineers, and manufacturers. It enhances collaboration and understanding across different teams involved in the product development process.

Inspection Criteria Definition: GD&T symbols

provide clear guidelines for inspectors, as inspection criteria are already defined in the 3D model. This reduces the chances of misinterpretation and ensures consistent quality control.

Virtual Condition and Tolerance Stack-up Analysis: With GD&T in MBD, engineers can perform virtual tolerance stack-up analysis to evaluate the cumulative impact of tolerances on assemblies and ensure proper fit and functionality.

2.4.2 Tolerance stack up analysis
MBD facilitates automated Tolerance stackup analysis using software as the dimensions with their allowable variation in tolerances are incorporated in 3D models which leads to quicker & better quality designs first time without adverse effects of tolerance accumulation and consequently faultless fits of parts during assembly without rework.

2.4.3 DFMA - Design for Manufacturing and Assembly
MBD combined with incorporation of Design for Manufacturing and Assembly (DFMA) best practices like Part - to - Part Indexing leads to better visualization of design intent at manufacturing and assembly stages.

2.4.4 Inspection through 3D scanning
MBD facilitates the inspection though a 3D scanner as the 3D model in MBD has all the product information like geometry along with its datums and tolerances which help in faster creation of deviation reports compared to manual inspection using a 2D drawing.

2.5 CASE STUDY OF IMPLEMENTATION OF MBD FOR PROTOTYPE FIGHTER AIRCARFT
The methodology followed in implementation of MBD for a fighter aircraft in the generation and release of MBD models for manufacturing and other downstream activities upto the design phase is presented in this paper.

Previously before implementation of MBD, the 2D drawings are generated from using 3D models using CATIA V5 R19 and released in ENOVIA / VPM environment. This design practice does not involve extensive use of GD&T symbols. The tolerances which are indicated in the drawings, refers to the tolerance standard, and other drawings office manual standards.

Initially three methods were considered for the generation of 3D models with MBD data All the three methods of execution with their relative advantages and disadvantages are listed below.

Method 1: 3D Models with all dimensions without GD&T symbols Dimensions are added to 3D model using FTA module in CATIA. However the GD & T symbols will not be indicated on 3D models, all the other attributes such as drawing notes, Material specification, finish, Non Destructive Testing etc would be annotated in MBD. The existing method of tolerancing will be continued to use in this method of MBD.

Advantages:

a. MBD models will look similar to the existing 2D drawings
b. All the information which was available in drawing title block will be available in MBD model.
c. Release of MBD data models will be in less time compared to method 2 & 3, as it does not involve GD & T symbols.

Disadvantages:

a. Change in culture would be required in the way part is fabrication, inspection, tooling, assembly, etc as it is different from the earlier practice.
b. Requirement of additional hardware and software at the Manufacturing. Assembly, Inspection, etc centers to read the 3D Models in MBD format.

Method 2: 3D Model with Only GD&T Symbols and no manufacturing dimension No Dimensions are added to 3D models, however all relevant GD&T symbols are required for the fabrication and assembly of the part will be indicated on 3D models. If the dimensions are required, the user

(Manufacturing, assembly, inspection, tooling, etc) can directly measure from the 3D model and obtain the data. All other attributes such as drawing notes, Material specification, finish, NDT etc would be annotated in MBD. The tolerances will also be indicated on the model.

Advantages:

a. 3D model becomes the Master, and it is used for all the activities.
b. MBD models will carry all the GD&T and tolerance data.
c. Fabrication will be done directly using the 3D models, reduced chance of misinterpretation of dimensions.
d. Tooling. Inspection, etc groups can measure the dimensions directly on 3D model, and obtain the data as required for them.

Disadvantages:

a. Additional training on the GD & T required for the shop floor technicians for reading the MBD models.
b. Drastic Change in culture would be required, as the model does not carry any dimensions.
c. Requirement of additional hardware and software at the Manufacturing, Assembly, Inspection, etc centers to read the 3D models in MBD format.

Method 3: 3D model with GD & T symbols with Critical Dimensions (Minimum dimensioning)

This Minimum dimensioning method is a blend of both Method 1 and Method 2, to maximize the advantages of both. In this method only critical dimensions with tolerance are added to 3D model using FTA module in CATIA along with all relevant GD & T symbols. All other attributes such as drawing notes, Material specification, finish, NDT etc would be annotated in MBD.

Advantages:

a. 3D model becomes the Master, and it is used for all the activities.
b. MBD models will carry all the critical dimensions required for Fabrication, inspection and assembly along with GD&T and tolerances required to completely capture the design intent.
c. Fabrication can be done using the 3D models, error due to dimension measurement by technician on 3D models are reduced.
d. As the required / inspectable dimensions are shown in 3D model, Tooling, Inspection etc groups need not extract the data from 3D models

Disadvantages:

a. Additional training on the GD & T required for the shop floor technicians for reading the MBD models.
b. Drastic Change in culture would be required, as the model does not carry all dimensions.
c. Requirement of additional hardware and software at the Manufacturing, Assembly, Inspection, etc centers to read the 3D models in MBD format.

For the execution of the project, Method 3, i.e. 3D models made in CATIA V5 R19, with the critical dimensions which are essential for the fabrication, assembly, inspection, tooling, etc are indicated with tolerances along with relevant GD & T symbols are implemented. The methodology of implementation with limited dimensioning was explained to Quality assurance and their concern regarding inspection with KCs was addressed by the proposal to use Hand held 3D scanners for Inspection of parts with contour wherein the manufacturer& inspector will be able to measure directly from 3D MBD model. The method involves three steps a)scanning the part b)CAD comparision c)Deviation check to ensure dimensions within tolerances specified.

Suitable region on the aircraft to implement pilot project was selected including both sheet metal parts and machined parts.MBD implementation in Composite parts was not carried out at the pilot project level due to complexities involved in modelling and time constraints in customization and is planned to be implemented in the next phases of MBD implementation.

For Sheet Metal parts (Non contoured parts)

a. All dimensions which can be measured will be provided in MBD.
b. Joggle dimensions will be provided from the part edge to the edge of the fillet.
c. No dimensions will be given for CH, PH, TH

For Sheet Metal parts (contoured parts)

a. Minimum dimensions will be provided in MBD.
b. Part surface will be controlled using suitable profiletolerance
c. Part edge boundary will be controlled using appropriate profile tolerance of
d. No dimensions will be given for CH, PH, TH
e. No extra key holes will be provided. Necessary drill templates to be developed for precision drilling of CH, TH, EH

For Machined parts (Non contoured parts)

a. All dimensions which can be measured will be provided in MBD.
b. No dimensions will be given for CH, PH, TH

For Machined parts (Contoured parts)

a. Only critical dimensions will be provided in MBD.
b. Part surface will be controlled using profile tolerance
c. No dimensions will be given for CH, PH, TH

After completion of the project, the experience gained from this would be used to scale up the MBD process.

Before implementation of MBD process training was given to the design personnel including the following training areas

a. Geometrical Dimensioning & Tolerancing
b. Tolerance stack up analysis
c. Design For Manufacturing and Assembly (DFMA)
d. MBD Process
e. Tools for MBD - FTA etc.

2.6 INFRASTRUCTURE REQUIREMENTS

With the absence of 2D drawings. the complete development process will be paperless and all the manufacturing, assembly, integration and inspection groups need to rely on the 3D model. For accessing and reading 3D model in place of 2D Drawings, a good IT infrastructure will be necessary - particularly in Production Engineering.

Requirements assessment with the total hardware requirements (long term and short term) along with location information and software requirements were captured in the form of actual use cases from each department. These use cases are tabulated in Table1. The use-cases projected by various groups has shown that most of the manufacturing groups need to access the right design data for manufacturing and visualizing the 3D Data with ease. Software tools/modules necessary to meet the user requirements were evaluated. Open and free visualization tools like Acrobat Reader can read the 3D PDF files and provide the visualization and measurement features necessary to meet requirements projected by users. Similarly, free visualization tool CATIA composer player provided by OEM of CATIA (M/s. Dassault Systems) found suitable for visualization of SMG data (proprietary format) files.

For visualizing CAD data, light weight formats 3D PDF (open) and SMG (from OEM of CATIA) were found to be suitable formats .

Table 1. MBD uses cases for various stakeholders

Department	MBD Use cases
Design Departments	• To create MBD models with dimensions • To create the MBD views and captures • To rotate pan and zoom the MBD model • To measure dimensions • To create sections for clarity on MBD model • To incorporate Information in title block and notes

Department	MBD Use cases
Manufacturing Departments	• To view MBD with dimensions • To view the MBD views • To rotate pan and zoom the MBD model • To measure dimensions that are not marked in MBD model by design • To take sections to get clarity on MBD model • To read information from title block and notes
Methods engineering	
Machine Shop	
Sheet metal shop	
CNC shop	
Tool Room	
Inspection Departments	

In view of the above assessment , a plan was made for augmentation of the infrastructure inclusive of Hardware requirements in terms of Workstations, PCS and clients for Production Engineering, Manufacturing and Assembly shops, Inspection department and associated offices of ORDAQA, and augmentation for Design groups & Software requirements to facilitate the manufacturing to access MBD Designs.

2.7 CHANGE MANAGEMENT IN MBD

One of the key advantages of MBD is its ability to streamline change management. In a 2D drawing-based environment, making even minor design changes can be relatively time consuming as it often involves updating and processing mutilple files like updated model, drawing and change notice. The process is also error-prone and incomplete with possbility of omissions as it involves updating change notice document manually. In contrast, MBD centralizes all design data in a single 3D model, making it easier to initiate, track, and implement changes. When a change is required, it can be made directly within the 3D model, and the associated annotations and dimensions are automatically updated, reducing the risk of discrepancies and costly errors and reduces the likelihood of miscommunication and ensures that all stakeholders are working with the most up-to-date information. MBD systems often provide detailed change tracking features, allowing users to see exactly what was changed, who made the change, and when it was made and thus facilitates a clear audit trail, enabling to track the history of changes and the individuals responsible for each modification. As stakeholders can easily compare different versions of the 3D model and evaluate the impact of proposed changes, it is very effective during design reviews.

In earlier 2D environment change notice consists of description of changes in Model, drawing views, title block and notes etc entered manually. In the MBD environment shown, the comparison of older version with newer version is depicted in the change notice with default generated color coding note. The other notes and information shall be generated from Enovia VPM environment without manual typing in MBD environment which avoids manual errors.

The benefits of MBD in change management can be summarized as reduced risk of errors, detailed change tracking ,better version control and better configuration management. Thus Embracing MBD enables the implementation of robust change management improving efficiency and quality in product design and manufacturing. Furthermore, integration with Product Lifecycle Management (PLM) systems provides a holistic approach to managing product data throughout its lifecycle, from initial design to manufacturing and beyond, ensuring that changes are managed consistently and comprehensively.

2.7. Limitations and Challenges in Implementing MBD

Creating MBD process considering requirements of all downstream applications

- Initially takes more time for designers, manufacturers and inspectors to adapt to MBD.
- New technology resource needs- licenses, trained personnel etc.
- Upgrading infrastructure to handle new tools/process/procedures
- Training & infrastructure provision for vendors & all stake holders to visualize& interpret MBD models
- Matching facilities to fabricate &inspect parts with MBD models- Hand scanners to inspect MBD models. Etc.

- Data content - downstream users need to be confident that the MBD datasets will carry the drawing's core and the required management elements like revision history, title block, zoning etc.
- Data presentation—Engineering drawings follow international standards in terms of data organization and structure and the same norms exists for MBDs.
- Data accessibility and visualization- The majority of downstream users (including suppliers and customers) do not have access to CAD software, and therefore a visualization tool that allows them to read and use MBD datasets will have to be adopted. All stakeholders should have the proper software tools at their disposal and need to be trained to use it. This leads to an increase of responsibility which can over strain the users.
- Data management—an appropriate method must be put in place in order to manage and record revisions of MBD datasets;
- Data security—a mechanism that incorporates security features (confidentiality, authentication, integrity and non-repudiation) when accessing, exchanging and interacting with MBD datasets will be required.
- Data retention—typically only 2D data is stored and used for legal purposes. The risk exists that once a particular CAD system is chosen, the dependency on this system will lock every stakeholder in to the ecosystem of the CAD vendor. This results in uncertainty about the lifespan of the proprietary file format used by the CAD system. This has an impact on the data retention policy of a company. A firm must be confident that the design data will remain available for a long time.

III. RESULTS AND DISCUSSION

With the incorporation of MBD, better part visualization and Interpretation resulted as shown by MBD views for a machined part example and sheetmetal part example in Fig 3, Fig 4 respectively.

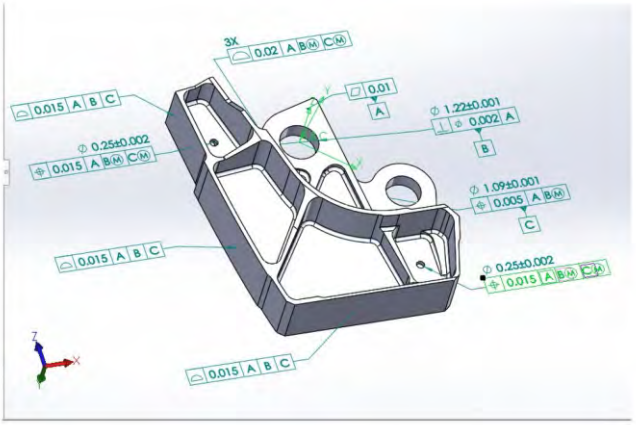

Fig 3. An example for machined Part in MBD
(Image credit:DSsolidworks)

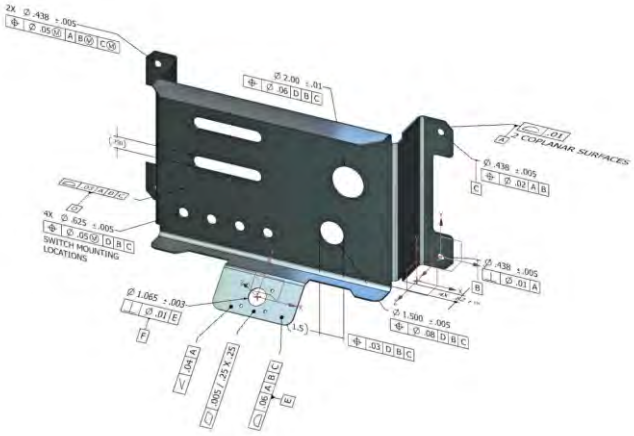

Fig 4.An example for sheetmetal Part in MBD
(Image credit:NIST)

With the incorporation of MBD, Model drawing discrepancy errors were eliminated with zero scope for Human errors with no duplication.

With the incorporation of MBD in a prototype fighter aircraft involving approximately 3000 parts, Design cycle times have reduced upto 30 % due to avoidance of duplication of 3D to 2D conversion as shown in Fig.9.

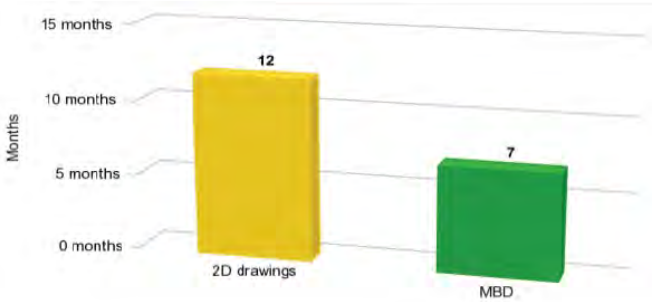

Fig 9 .Reduced Design cycle time with MBD

The following Table .2 lists the differences between 2D drawings and MBD

Table 2.COMPARISION TABLE MBD AND 2D DRAWINGS

Sl No	Description	2D Drawing	MBD
1	Visualization	Satisfactory	Excellent
2	Design Effort	More	Lesser
3	Design cycle Time	More	Lesser
4	Mfg. Interpretation	Scope for ambiguity	No Scope for ambiguity
5	Chance of Errors in Design	More	Less
6	Data Duplication	Yes	No
7	Machine readability & 3D scanner for Inspection	Not facilitated	Facilitated
8	Integration to PLM	Difficult	Easy
9	Infrastructure requirements	Lesser	More
10	Change management	Difficult	Easy

IV. CONCLUSION

Companies that still use 2D drawings in their product life cycle are doing more than simply ignoring the increased productivity that comes from streamlining their models. They are also failing to provide their customers the best, most cost-efficient products and services that can only come from implementing a single, comprehensive digital model that all stakeholders can effectively utilize. Moving away from 2D renderings (or even a hybrid approach with a 2D original and 3D model) to a completely digital design solution offers a wide range of benefits. Companies that incorporate digital GD&T with model-based definition (MBD) 3D models can create more accurate representations that speed up the design and production processes, reduce waste, and improve communication and collaboration across all teams involved in the design and manufacturing process.

The findings of the paper suggest that an implementation of MBD is essential and that the benefits outweigh the predicted challenges that come with an implementation.

Benefits of implementation of MBD can be summarized as below:

- Improved data quality due to single state data. e.g elimination of errors occurring in 2D drafting in conversion from 3D.
- Shorter cycles time for Design
- Better communication of design intent to related downstream activities like methods engineering and manufacturing.
- Leads to employees' focus on value-added work
- Faster access to product information
- Better change management
- Improvement in communications with suppliers

Acknowledgment

PLM Team, ADA and Dassault systems Team for their support and customization of MBD Modules.

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Optimization of INS/GPS harmonization on Military fighter aircraft

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Abstract - Harmonization is the terminology applied to the procedure used to orient the on-board display, sensors and weapons i.e., Head-up Display (HUD), Radar, Inertial Navigation Systems (INS) and GUN armament etc. to the aircraft reference axes. The harmonization error is measurement of disparity between the system reference axis & aircraft reference axis. These errors usually occur by cumulative stacking of tolerances, assembly deviations of other respective structure deviations. The display & Sensor units are Line replaceable units (LRU's), hence harmonization error of mounting platforms in roll, pitch and Yaw axis with respect to aircraft reference axis is compensated either electronically through software or mechanically using suitable shims. Traditionally the harmonization error computation is carried out using optical metrology, including telescopes and target board positioned at predetermined distance from aircraft. Predefined attachment points called datum points (hard points) are used for placement of target board in aircraft reference frame. Both aircraft and target board are leveled using inclinometers. Target board has fiducials for the LRU's to be harmonized with respect to aircraft datum. Precise optical jigs are used for computation of Harmonization error. The optical jigs are specifically designed based on system installation on the aircraft and unique for aircraft kind. The projection of the optical jig telescope on the system fiducial is used for measurement of Harmonization error of the system platform usually called as mounting tray. The Harmonization error is either reduced using mechanical shims or electronically compensated as per individual system capability.

Keywords - Inertial Navigation System, fiducial, harmonization, optical Jig.

I. INTRODUCTION

Harmonisation is carried out on airframe and onboard equipment to ensure the reference lines of the airframe and the equipment are aligned as per design specifications. In general aircraft airframe are levelled using theodelite system. This is a manual process and involves time to set all the systems. In order to make the procedure effective and simple, Laser tracker is greatly helpful. When an aircraft is used for longer period, the alignment of structure and onboard equipment may get disturbed resulting in sub optimal performance of aircraft. Also, the misalignment occurs during replacement of system units, other structural elements, during servicing, over hauling, hard landing etc.

Currently the levelling and combining the system units to a common reference frame is done manually and time consuming process, harmonisation with laser tracker is effective method to correct and bring the deviations encountered in system unit installations. INS harmonisation is vital and also needs to develop a quick harmonisation for the INS system to meet the mission performance during combats and also to have effective aircraft functioning.

Aircraft in general consists of head up display HUD, Inertial navigation system (INS), Gun and Radar system and these required to be harmonized. Among these INS were harmonized using Geographical references in yaw axis and aircraft leveling reference for Pitch & Roll axis. The Aircraft reference used for INS/GPS harmonization was different from Aircraft reference used for harmoni-

zation of other systems. Due to inherent manufacturing tolerances in aircraft reference points, the variable residue of harmonization error up to 4 milli radians was observed across the aircrafts.

II.OVERVIEW OF INERTIAL NAVIGATION SYSTEM

Navigation is the determination of a physical body's position and velocity relative to some reference coordinate frame or coordinate grid. An inertial navigation system utilizes the inertial properties of sensors mounted on the vehicle to execute the navigation function. Inertial navigation system is capable of continuous determination of vehicle position and velocity without the use of external radiation or optical information. Inertial navigation systems have obvious advantages for military applications, the trend toward automatic flight control systems in civil aircraft applications will require an extensive reliance on inertial systems.

III. EXISTING METHODOLGY OF CALIBRATION

The existing procedure of assessing the relative errors in INS/GPS requires extreme effort and probability error in data capturing will be huge. The procedure comprises marking North-South reference on ground beside parked aircraft as shown in Fig.1 measuring the coordinates through Laser tracker or theodelite. The INS itself gives the position in terms of translation and rotation vectors with respect global North-South earth frame. The INS unit positioned on aircraft axes is being measured taking North-south line marked on the ground. The INS positional data is captured through electronically. The mechanical position of INS unit is measured either using laser tracker machine or theodolite system with local reference as the line marked. And the relative difference in measured as error in the positional accuracy of INS unit which is mounted on the INS tray of the aircraft. The complete procedure may give errors in the data to be provided to the software for the correction.

To overcome the lengthy procedure and inaccuracy in error capturing, a simplified procedure was evolved and product is developed named as INS optical Jig. The optical Jig is designed to meet the INS requirements and designed ergonomically so that it can be easily assembled on to the aircraft and has no obstructions to capture the positional points projected on target board through optical instrument

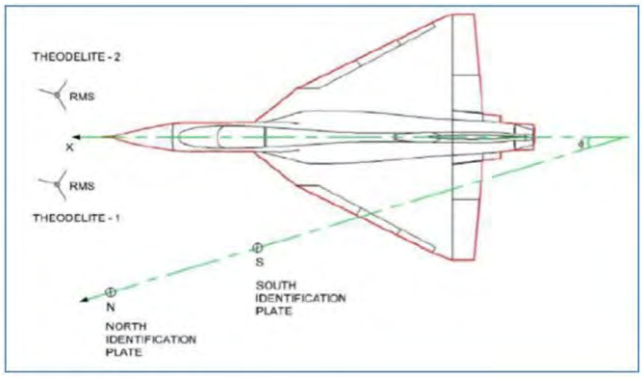

Fig.1, Aircraft on ground with North-south reference marking

IV. DATUM CAPTURING USING LASER TRACKER

The laser tracker is being used to arrive the aircraft reference plane and centerline axis. The aircraft is parked on the level ground, a place where the set up for harmonization procedure is established. The aircraft is jacked and leveled using clinometers as shown in Fig.2

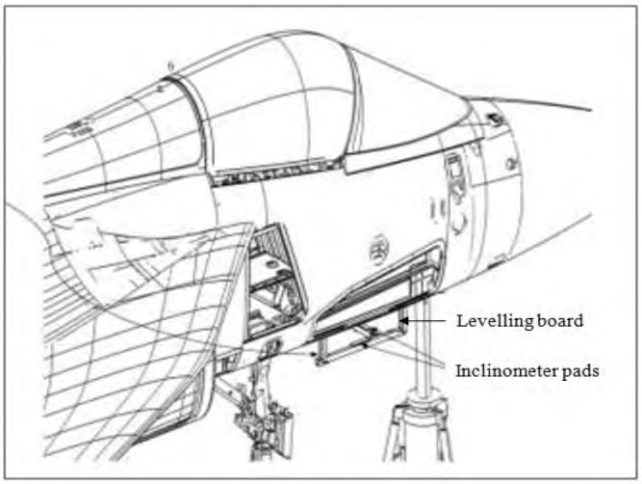

Fig.2, Aircraft on Jack and levelling board

Remote Coordinate Measurement System (RMS) for placement of Harmonization board with respect to aircraft reference coordinates. Laser Tracker based RMS is being used for establishing aircraft reference coordinates system. The laser tracker is placed near the aircraft, marked as local

reference point. The input for the calibration is the three design hard points on the aircraft termed as datum points. In general, two of these datum points will be on wing, one on LH side and one on RH side. The third datum point usually at forward and mid of other two points. These three points were precise values to the aircraft. The three points were captured through laser tracker using SMR probe with base as the laser tracker local coordinate position. The datum points were fed to laser tracer software which interpolates through translation and rotation coordinate transformation. This brings the laser tracker system to aircraft coordinate system of measurement. The aircraft reference plane (FRL) and centre line of aircraft will be achieved. Once the laser tracker is in aircraft reference, the target board is placed at predetermined distance and aligned to FRL and centre line axis with the available markings on target board with ensuring the following points,

I) Position the harmonization board in X direction
ii) Level the Harmonization board in roll and pitch axis using spirit levels.
iii) Adjust FRL point, Y and Z within 0 ± 1 mm on harmonization board (target board). Note that these values may change as per aircraft requirements
iv) Record Final X-Position of harmonization board.

Now the aircraft and Target board faces each other and this completes the preliminary procedure set up to go ahead for the harmonisation procedure of all the required sensor and navigation units. Fig 3a illustrates the set up for Target board and aircraft along with laser tracker. Fig 3b shows the datum points P, S and T.

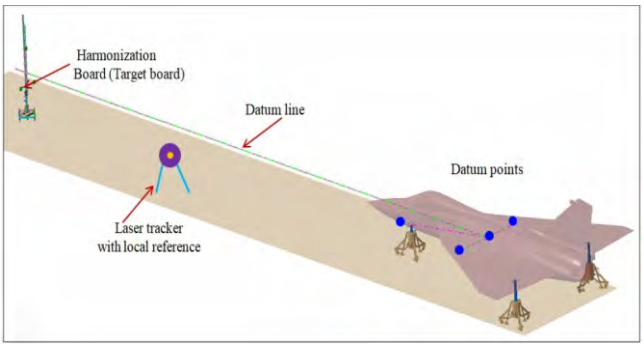

Fig.3a, Datum Capture on aircraft using Laser Tracker

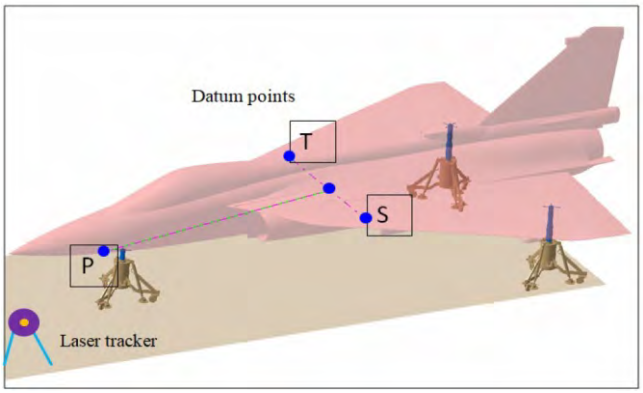

Fig.3a, Datum points available on aircraft, P, S and T

V. INS TOOL (OPTICAL JIG) DEVELOPEMENT

The physical interface dimensions of INS unit and INS mounting tray have been captured precisely through reverse engineering and designed optical Jig. The design point is achieved respecting the assembly constraints on the aircraft and to have a clear view from the aircraft to the target board. The closed tolerances have been maintained to avoid any error in data capturing. Optical Jig is manufactured and assembled. The tool has under gone several stages of CMM inspection to achieve closed tolerances and to maintain desired surface roughness and to have locating pin axes alignment. The tool has V-slot for bore sighting tool. The tool is designed such that bore sighting tool, once placed on the V-slot, the sighting point matches to the INS design point. The tool is calibrated at Lab level establishing harmonization set up points. Any small delta error in the tool is corrected in the bore sighting tool and is locked. The tool along with bore sighting tool will be placed on INS mounting tray, which is fixed to aircraft for further capturing of INS points. The Fig.3, shows Fabricated INS tool (optical Jig) for harmonisation and the tool under CMM inspection..

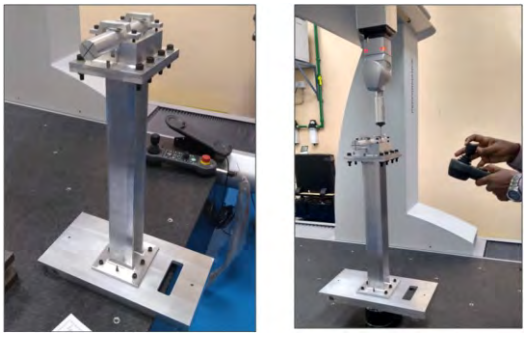

Fig.3, Fabricated INS tool (optical Jig) for harmonization

VI. METHODOGY OF ERROR CAPTURING

The requirement of Harmonization is to have common reference for all sub systems. The target board has all fiducial points with respect to aircraft reference and is in line with aircraft reference. The INS unit will be disassembled from the INS tray and The INS optical jig is placed over the INS mounting tray. Through the bore sighting tool, the crosswire centre point falling on grid sheet of target board is marked. The Y-shift and Z-shift of the projected point is noted. This shift in value gives error in Pitch and Yaw of the INS mounting tray. The error in roll is measured by placing the clinometers on the flat face of INS tool base. The error points fed to the aircraft software for the correction of INS positional coordinates. The projected point if INS on target board is shown in Fig 3.

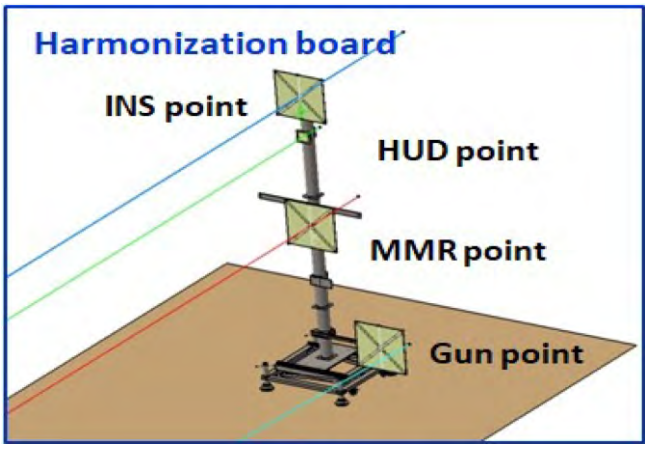

Fig. 4, Viewed point of INS on harmonization board.

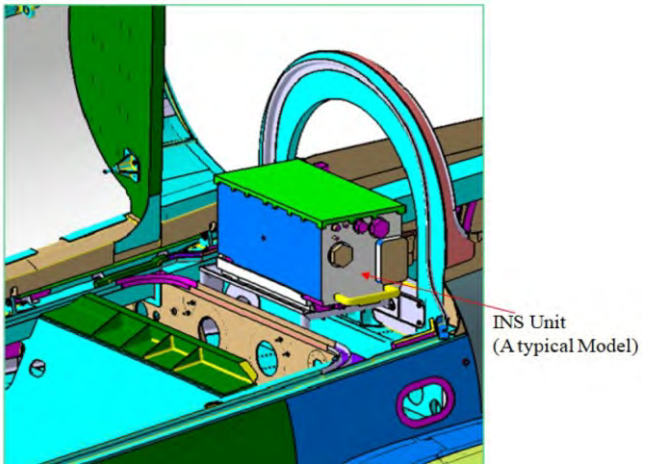

Fig.5, INS Unit model on the aircraft

The INS unit (a typical model) on the aircraft is shown in Fig.5. The installation INS tool after removal of INS unit and its interface with mounting tray projection pins is shown in Fig.6. Once positioned, the tool base is locked with bolt to arrest any play during measurement.

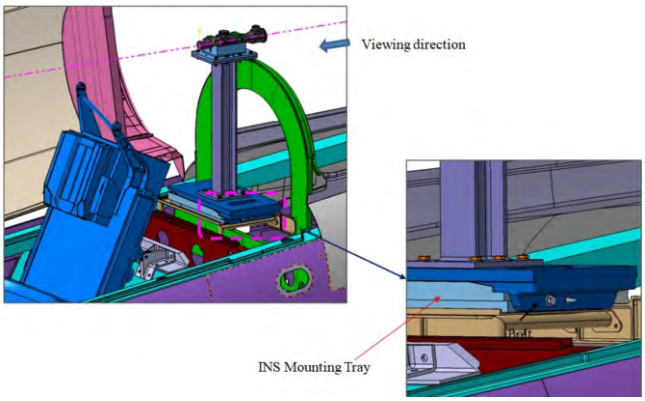

Fig.6, INS tool position on the aircraft

VII. OUTCOME AND SUMMARY

The error data generated with current system of calibration for INS has been compared with error data captured using the new procedure. The procedure is carried out on several military series production aircrafts to assess the level of accuracy achieved. The developed product that is calibration through optical jig has become effective and simple to adopt and the procedure is acceptable to the user. The residue Harmonization error is not observed during weapon aiming & delivery.

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Increasing Efficiency of Aircraft Ground Handling Operations

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Abstract / Executive Summary - Operations on an airport tarmac and carrier flight deck are carried out in a constrained time and space critical environment. It is therefore, essential to optimize the mission readiness activities with efficient planning and resource allocation to generate the desired sortie rate for efficient operations. To manage the sortie and traffic load it is incumbent for military and civil operators to launch the aircraft(s) for mission in shortest possible time by reducing the Turn Around Time (TAT). This paper analyses the challenges faced by ground crew during ground handling operations impacting efficiency and mission readiness. The authors try to investigate the root causes and discuss the effect of human factors and human engineering (HE) compliant design in reducing fatigue and accidents attributable due to human errors. Benefits of enhanced Ground Handling Equipment (GHE) / Ground Support Equipment (GSE) based on electric power and universal design with autonomous features are suggested for improved performance and cost-effective operations. Autonomous GHE/GSE with anthropometry and human ergonomic design criterion are developed and demonstrated on a 4th generation aircraft for qualitative improvements and quick turnaround time. Mathematical modelling and field trials are done to evolve an empirical formula to calculate and validate the TAT. Improvements of up to 50% in work efficiency and 25% reduction in TAT are achieved with innovative design and manufacturing of GHE/GSE. Use of improved GHE/GSE with autonomous features have a great potential in improving the efficiency of aircraft ground handling operations and long-term cost and carbon credit benefits.

Keywords - Anthropometry, Ground Handling Equipment (GHE), Ground Support Equipment (GSE), Human engineering (HE), Turnaround time (TAT).

I. INTRODUCTION

Ground handling operations on any tarmac or flight deck comprise of a series of operations performed on the aircraft for mission readiness. The ground handling and preparation activities are required to be planned and optimised as per sortie requirements and number of aircraft required to be prepared for the mission. Tactical aircraft generally carry their armament load, special purpose pods, fuel tanks, to name a few, externally on the fuselage. The traditional and conventional GHE/ GSE (Tractors, tow bars, loading trolleys/dollies) very often do not suit and fit into restricted space on tarmac and flight deck. Further, with integration of newer weapons having different profiles and clearances on the legacy fleet, the conventional GHE/GSE lack the specific articulations and anthropometric requirements for seamless integration.

It is therefore essential to understand the human ergonomics and human factors while selecting and deploying new support equipment for reduced human errors and reliable ground handling [1], [2]. The efficiency of ground handling operations can be improved by factoring good ergonomics and human engineering in the design with autonomous features. Military GHE/GSE should factor the Performance Shaping Factors (PSF) to reduce fatigue and to enhance crew efficiency for quick turnaround. Further, introduction of GHE/GSE with enhanced features have proved to be cost beneficial by at least 10%, over a

long period, in energy saving and in reducing the negative impact of carbon emissions on the environment [3].

The present paper is organised as follows: Section 2 explains the aspects of military aircraft ground handling operations, Section 3 analyses the problem statement, Section 4 presents the results and discussions and proposed improvements. Recommendations and Conclusions are presented in Sections 5 and 6 respectively.

II Military Aircraft Ground Handling Operations

Military operations are very different and challenging than civil operations due to constraints of "bare and basic" equipment and minimal support available to sustain operations. Military aircraft mission readiness as per desired configuration are a challenge for ground crew due to the environment and minimal support facilities.

These aircraft in tactical role frequently operate from outstation bases restricting their GHE/GSE and the role equipment due to airlift constraints. With the available GHE/GSE, it is difficult to predict "which may" and "what may" go wrong during aircraft preparation.

Towing and pushing military aircraft present unique challenges. These aircraft need to be positioned and prepared for different roles and missions and require different support services. The loading and arming of different stations and hard points require a well-trained crew and properly designed loading equipment. The conventional GHE/GSE like tractors, tow bars and weapon loading trolleys are usually adapted from the existing aircraft inventory supplied by the OEM and are rarely customised. Most of this vintage equipment are bulky and demand large manpower for positioning them thereby extend the activity preparation time. This equipment, being voluminous and bulky, are usually not human engineering compliant, thereby, posing a huge penalty on efficiency, weight and volume for airlift squadrons. It, therefore, needs to be accepted that there cannot be too many equipment and variations of GHE/GSE on the tarmac and flight desk. Multiple equipment would occupy large tarmac and deck space requiring multiple set of crews for operations in an already constrained environment. Military environment necessitates "bare and basic" equipment and minimal logistics to optimise workspace and airlift requirements [4], [5].

Ground handling challenges

It is well known that Indian Armed Forces hold a sizable inventory of legacy as well as new generation aircraft of Russian and Western origin. Operating and maintaining these multi-generation and technologically varied systems is a huge logistical and engineering challenge.

The military aircraft flightline operations can be visualised as a sequence of "Over wing" and "Under wing" activities (Fig 1). Over wing activities comprise of aircraft towing/pushing to/ from tarmac, refuelling, communication checks, power and ECS connections, O2/N2 charging, preflight functional checks and DI activities for preparation of flight. Similarly, under wing activities involve fitment / removal of role equipment, loading and arming of stores,movement of ground handling equipment and safety checks up to aircraft start up andsee off.

These activities are required to be carried out each time for aircraft mission readiness and post flight recovery. While the time of activities for DI checks is dependent upon the maturity of ground operations and specific activity cards for the fleet, there exists scope for cutting down tarmac time during pushing / towing, armament loading and arming with improved GHE/GSE and autonomous features. In the case studied as shown in Fig.1, First Flight Service (FFS) time is observed as 2 hours and TAT is 1 hour 15 minutes, without any armament loading, configuration changes and arming activities. Action for armament related activities commence after the aircraft is declared functional and cleared for armament mission.

Under the present study on the aircraft, loading and arming time is 15 minute per station with a set of trained crews and the available GHE/GSE. As per user interaction at HAL and operating units, the armament loading and arming activities are highly constrained due to inefficient GHE/GSE

design and ergonomics. The activities are conducted by "trial-and-error" methods which are inaccurate and risky. To compensate for fatigue and poor ergonomics, the manpower in each gang is increased thereby making operations costly, time consuming and inefficient. As per the study, there exists huge scope for improvements and achieve quicker TAT and armament mission readiness by improved design of GHE/GSE and use of autonomous tugs for pushing and towing of aircraft and other associated equipment for flight readiness.

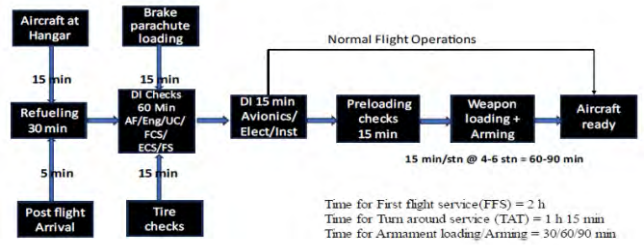

Fig. 1 Sequence of activities: Aircraft preparation for FFS and TRS

The details of equipment, manpower, processes, management and environment involved in ground handling and preparation activities for FFS or TRS is a step-by-step timed process as depicted in the Ishikawa diagram (Fig. 2). The root cause analyses for delays and effects on human ergonomics and improvements thereof are studied based on the activities breakdown and documented during the study.

Fig. 2 Ishikawa Diagram: FFS and TRS

III Analysis

Motivation for this research is based on experience and interaction with the users on the gaps and challenges faced during the aircraft preparation and ground activities. Focus was on human factors and ergonomics with human engineering concerns in existing GHE/GSE. Ground handling activities during configuration changes for armament missions are selected for study in relation to human performance metrics (gang size, accessibility and accuracy, fatigue and activity completion time, comfort and risk of injury). The study focussed on activities and procedures with existing GHE/GSE and with focus on human factors effects on crew efficiency and TAT. Modified design with concept of universalisation and autonomous features are conceived, developed and subjected to field trials. Analysis has been done with focus to improve work efficiency by HE complaint design of GHE/GSE towards improving:

- Towing and pushing operations
- Configuration changes, loading and arming activities.
- Rapid and safe operations
- Crew safety and fatigue reduction

Human factors and design challenges

Our aim is to identify and study the compliance of human engineering criterion [4] to existing GHE/GSE and its effect on human performance and reliability of personnel-equipment combinations [5]. Human Factor Science (HFS) comprises of multidisciplinary fields incorporating psychology, engineering, industrial design, operations research, anthropometry, statistics, to name a few. HFS is a term that covers the science of understanding the properties of human capability and its application to design and development of system and services. There are many disciplines that comprise human factors affecting aviation technicians. However, for present study, we remain focussed on two disciplines i.e., Anthropometry and Safety engineering compliance in ground handling operations. Anthropometry reflects the effects of environment, space-reach-dimensions weight of GHE/GSE and design ergonomics on ground crew. A poorly designed and developed equipment increases fatigue and effects the crew efficiency and time of activity. Safety engineering reflets in design of facilities, handling devices and equipment used for pushing and lifting critical stores. Aviation environment requires design of GHE/GSE and tools to reflect the essential considerations as per the mnemonic PEAR in the HF

model for assessing and mitigating human factors in aviation maintenance. The letters PEAR stand for four important considerations for human factors which are People who do the job, Environment in which they work, Actions they perform and resources necessary to complete the job [6].

PEAR Deficiency ⇨ Human Error ⇨
Intentional or Unintentional ⇨ Active or Latent errors.

It is concerning that an aviation ground crew working under stressful environment may contribute unintentionally towards active errors and latent errors due to intentionally working with unsatisfactory GHE/GSE equipment.

IV Results and Discussions

The studies were conducted on a 4th generation aircraft of IAF inventory mapping the routine and armament specific tasks on the flightline. Measurements during preparation of aircraft for flight readiness and during configuration changes and stores loading and arming were carried out for seven different types of stores and carriage equipment. The measurements for monitoring the activity timelines and manpower required for various activities with conventional and improved methods were conducted in parallel and same are tabulated at Table 1. It is deducted that the military aircraft preparation and readiness time for armament mission can be forecasted by an *empirical formula*.

Ta = K1 + K2. ŋ + K3. R, where
Ta = TAT in minutes
K1 = Over wing activity time constant in minutes
K2 = min/station for loading and arming
ŋ = number of stations/stores
K3 = minutes/meter for pushback/towing
R = Pushback/towing distance in meters

The study team conducted trial loading and arming activities simultaneously with existing GHE/GSE and the improved Universal Weapon Loading Trolley (UWLT) (Fig. 3) and push back by Autonomous Tow Tug (Fig. 4) to ascertain the fatigue and human factors and manpower demand and savings during loading and arming on a 4th generation aircraft of IAF. The results are tabulated in Table 1.

Table-1 Aircraft ground handling activities time motion study results

Procedure/Activity	Tractor + Towbar		Tow tug	
Excluding preparation work	Time	Crew	Time	Crew
Aircraft towing 300m	20 min	3+1	UT	1+1
	WLT	Crew	U-WLT	Crew
R/I Pylon Outboard (w/o elect work)	15 min	2+1	10 min	2+1
R/I Pylon Mid board (w/o elect work)	20min	4+1	13 min	2+1
R/I Pylon In board (w/o elect work)	45 min	4+1	30 min	2+1
R/I Pylon UF (w/o elect work)	60 min	4+1	45 min	2+1
R/I Drop tank 1200	25 min	4+1	15 min	2+1
R/I Drop tank 800/725	25 min	4+1	15 min	2+1
R/I of weapons @IB, MB, OB, UF	@ 15 min/station	4+1	@ 08 min/station	2+1
Laser guided bomb	30 min	4+1	20 min	3+1
R/I Laser Designator pod	30 min	4+1	20 min	2+1
Savings			25-33%	50%

From the results above it can be seen that there is 50% saving in manpower and minimum saving of 25% on the activity time, which is considered significant for mission preparation and quick TAT. The details of enhanced GHE/GSE are shown at Fig 1 and 2 respectively.

Fig. 3 Uinversal Weapon Loading Trolley

Fig. 4 Autonomous Tow tug

The complete study on aircraft ground handling operations is dependent on four variables namely the equipment, manpower, process and environment. Each operation in aircraft ground handling is interdependent, hence it may be noted that not every process or procedure may result in an increase in efficiency. However, the improvements in reducing TAT were noted on account of improved design for rapidity and safety of operations along with savings in crew strength and ease of operations.

The focus of research was on introduction of improved and enhanced GHE/GSE for improving the ground handling qualities for reduced footprint and improved manoeuvrability. With improve-ments in GHE/GSE design, pushing /towing and loading /arming activities could be improved with significant time and manpower savings without compromising the flight line safeties. The ground handling operations could be made more efficient, less stressful and human intensive due to improved human ergonomics and reduced noise and carbon emission. Significant cost and time savings were observed in activities involving aircraft push back with autonomous tug and readiness for armament missions using universal weapon loading trolley U-WLT [7].

V Recommendations

Based on the above study and research, further studies in aircraft ground handling activities for another fleet is possible with improved and customised GHE/GSE. There is a huge potential in cost savings during tarmac operations and mission preparedness with enhanced and autonomous GHE/GSE and Tugs.

VI Conclusion

Military aircraft aviation operations are very difficult and different. The operational tempo is high while there is high constraint on manpower. There is, therefore, a need for efficient GHE/GSE to reduce fatigue and free up working hands. Low quality and out of date equipment can be frustrating for operators and may result in high possibilities of human induced errors. The perspective of automation and human ergonomics complaint design is a prudent requirement. Reduction in manpower, carbon print and cost of operations is an unavoidable futuristic requirement which needs to be factored urgently. The new concepts proposed shall have the benefit of cost reduction by way of fuel and manpower savings, reduced carbon print and improved safety on tarmac. Overall, it can be stated that improvements in GHE/GSE design and changes in ground handling procedures will lead to significant reduction in TAT, manpower, running costs and carbon content for civil and military aircraft operations.

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Extended Abstract: Computer Aided Assembly Sequence Generation for a Hierarchical Product Structure of Aircraft Structural Assemblies

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Abstract/Executive Summary - The assembly process for the Aircraft involving thousands of components presents a challenge in creating all possible assembly sequences and finding the best feasible one. This paper addresses this issue, with an improved implementation of earlier research literature, considering the assembly constraints of, connectivity between parts/products (Liaison matrix), geometric interferences in approach directions and part/product stability, in the form of matrices. The proposed method further reduces the number of feasible assembly sequences with careful arrangement of all parts into hierarchical product structure having sub-assemblies (Level1) and sub-assemblies (level2). The matrices being used are obtained through pre-processing, clash analysis, and geometrical considerations. The CATIA VBScript is used for developing algorithms for generating the necessary matrices from CAD models as excel sheets. The generated excel sheets can be used for showing the assembly process visually.

Keywords - Assembly Sequence Generation (ASG), Angle Matrix (AG), Direction Matrix (DM), Geometric feasibility Matrix (GFM), Liaison Matrix (LI), Stability Matrix (STB)

I. INTRODUCTION

Assembly sequence planning is a pivotal phase in the manufacturing process, determining the order and the way individual components are assembled to create a final product. Efficient assembly sequence generation not only impacts production time but also influences the quality and costeffectiveness of manufacturing. Over the years, researchers and engineers have sought innovative methods to automate and optimize this intricate task, leading to the development of advanced techniques and algorithms.

Anticipating the problems of assembly sequence/ order before the finalization of design is a challenging problem, keeping in-view of material and operator travel distances. Preparation of data for visually verifying the assembly process is a tedious process. The large assembly (like aircrafts/ sub-marines, ships etc.) manufacturing organizations are facing the problem of quickly generating all the possible assembly sequences and visually verifying.

Certain amount of pre-processing input is required for automating the creation of all possible assembly sequences.

Our work builds upon the foundations laid by prior research in the field of assembly sequence planning. The knowledge-driven approach advocated by Lin et al. [1] and the rule-based methods proposed by Qian et al. [2] have provided valuable insights into generating effective assembly sequences. Additionally, the significance of geometric feasibility and stability, as emphasized

by Zhang et al. [3] and Bourjault [4], continues to drive advancements in assembly planning. Our work is also guided by insights from Bahubalendruni and Biswal [5][6][7][8], who have contributed innovative techniques for assessing feasibility and stability in robotic assemblies. The incorporation of automated systems, as explored by Romney et al. [9] and Makris et al. [10], represents a significant step toward enhancing the efficiency of assembly processes.

The methodology outlined in this paper extends the assembly directions along beyond traditional principal axes to the oblique directions in 3d space, offering a comprehensive approach to sequence generation.

This paper presents a methodology for assembly sequence generation that focuses on the efficient organization of subassemblies and their constituent parts. In the pursuit of this goal, we draw inspiration from various established techniques and computational tools. The proposed approach is geared toward the generation of assembly sequences that minimize geometric conflicts while ensuring stability in the final product. By classifying components into distinct levels (LV-1 and LV-2) and employing rigorous clash analysis, we aim to facilitate a systematic and intuitive assembly process.

2. ANALYSIS /Methodology

Detailed description of the proposed methodology for assembly sequence generation for sub assemblies and parts in it:

The current method involves the preprocessing of the product structure into the hierarchical arrangement of parts/sub-assemblies (as components) into multiple levels. The overall process is modified introducing the multi-level structure and the generation of liaison matrix and modified geometric feasible matrix with oblique directions (3 non-zero direction cosines along principal directions) including special cases (parallel to principal axes: x, y and z, parallel to Cartesian planes: x-z, y-x and z-y planes).

2.1. Liaison Matrix Extraction:

At a time two LV-1 components are first selected, and clash analysis is performed on them. If the clash value between two components (such as i and j components) is found to be 0, then the value in the liaison matrix for i and j components is set to 1. If the clash value is greater than 0 (clearance/gap), then the value in the liaison matrix for i and j components is set to 0 [5]. As clash analysis is performed on parts only, two cases between two components were observed:

Case I: In this case both the parts, of all the pairs between them, the contacts are observed, are belongs to the same component, it is not considered as the genuine contact, even if the clearance value is near zero. As none of the parts of the ith component has the contact with any part of jth component, a "0" value is assigned in the liaison matrix for ith row and jth column element. As shown in the Figure 1.a, the contacts 1 and 3 are within same component coloured red. And the contacts 2 and 4 are within the component coloured yellow.

Case II: In this case, the contact/s is/are observed between at least one pair of parts, where they belong to different components. The parts, of at least one pair, which are in contact are belongs to different components. As shown in Figure 1.b, there are 3 contacts (5, 6 and 7) where the parts of each pair belong to different component (coloured red and yellow), Hence the value "1" assigned in the liaison matrix for ith row and jth column element.

Following the completion of LV-1, the next step involves selecting all the parts within the LV-2

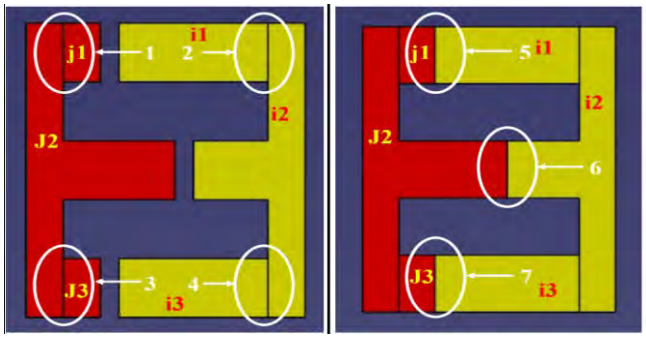


Figure 1.a and 1.b Conflict Possibilities

category that belong to the first sub-assembly of LV-1. Clash analysis is then conducted on these LV-2 parts. If the clash value between two parts (represented as the ith and jth parts) is determined to be 0, the corresponding entry in the liaison matrix for the ith and jth components is set to 1. Conversely, if the clash value exceeds 0, the corresponding entry for the ith and jth components is set to 0. This process is repeated for all subassemblies.

2.2. Interference Matrix (Geometric Feasibility Matrix GFM):

2.2.1. GFM Along Principal Axes:

Each time two components are selected, consider along the +ve y-axis, if component i can move without interfering with component j, then the value in the matrix at position (i, j) is set to 3. However, if component i clashes with component j, then the value is set to 0. To detect collision, after every unit move of component i, clash analysis is performed between component i and j [6]. This method is implemented in LV-1 and then LV-2 components.

As clash analysis is performed on parts only, when applied to assemblies/products, following cases between two components were observed:

Case A: If there are conflicts

Sub-case A1: At least one Conflict with First component Product.Name belongs to the name of the part in ith component AND Conflict. SecondProduct.Name belongs to the name of the part in a jth component.

Sub-case A1.1: In those all conflicts, if all conflict values are positive (clearance) then give a value "3" in the GFM for products indicating the first product can move without interfering with the second product.

Sub-case A1.2: In those all conflicts, if any single conflict value is negative (clash/interference) then give a value "0" in the interference matrix for products indicating the first product is interfering with the second product.

Sub-case A2: For all conflicts, Conflict. FirstProduct.Name AND conflict. SecondProduct.Name belongs to either ith component OR jth component then give a value "3" in the interference matrix for the first component can move without interfering with the second component.

Case B: If there is no conflict, then give a value "3" in the interference matrix for components indicating the first component can move without interfering with the second component. The values (1, 2, 3, 4, 5, and 6) are assigned to represent the principal axes: +x, -x, +y, -y, +z, and -respectively.

2.2.2. GFM Along Oblique Direction on principal Planes:

While implementing the assembly sequence generation macros on the complex assemblies (e.g., stub-wing of the aircraft), it became evident that certain components within the assembly did not exhibit geometric feasibility along the principal axes.

2.2.2.1. Finding pair of those components which leads to non-feasibility -

Those pairs of components that exhibit a '0' value in the Geometric Feasibility Matrix (GFM) for all six principal directions (+x, -x, +y, -y, +z, -z) signify that one component cannot move in any direction in the presence of the other. Within such pairs, the component with a higher number of '1' values in the Liaison Matrix (indicates that it is in contact with a greater number of components) is designated as the base component, while the other is referred to as the rotor.

2.2.2.2. Determination of Maximum and Minimum Values of a Component along an Oblique Direction:

When assessing the maximum and minimum values of a component along an oblique direction, it is important to note that these values can vary as the direction changes. In this methodology, limits are set based on the component's maximum and minimum values along the principal axis. Let us consider a 2D plane, such as the XZ plane. In this scenario, any component can be enclosed within a

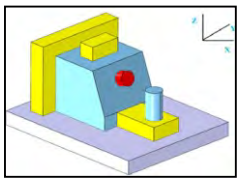


Figure 2. Oblique Model

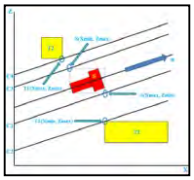


Figure 2a: Smin>=T1max and T2min>=Smax

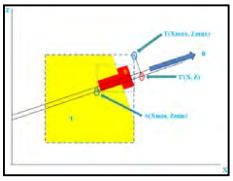


Figure 2b: S(Xmin) >=X and S(Zmin) >=Z

quadrilateral formed by four points: (Xmin, Zmin), (Xmax, Zmin), (Xmin, Zmax), (Xmax, Zmax).

Let us consider oblique model as shown in (Figure 2) in which we need find possibilities in which red component S can interfere with other component T1, T2, T3, T4 and T5 or not along the u-direction, forming an angle Θ with respect to the x axis.

Possibilities (Along perpendicular to u-dir and along y-axis) in which collision between components will not occur:

Possibility-1: Minimum Z value of component-S is more than or equal to maximum value of component- T1 i. e. C1 >= C2 (refer Figure 2a) or (S)Ymin>=(T1) Ymax.

Minimum and maximum values along perpendicular to u direction:

- The minimum value of component S is determined by the z-intercept of the line passing through the point S (Xmax, Zmin) parallel to udirection.
- The maximum value of component T1 is determined by the z-intercept of the line passing through the point T (Xmin, Zmax) parallel to direction.

Possibility-2: Minimum value of component-T2 is more than or equal to maximum value of component-S i. e. C4 >= C3 (refer Figure 2a) or (T2) Ymin>=(S)Ymax

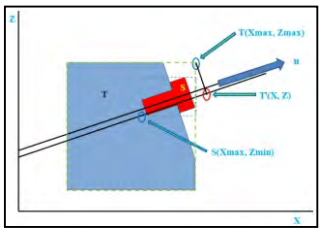
Minimum and maximum values along perpendicular to u direction:

- The minimum value of component T is determined by the z-intercept of the line passing through the point T (Xmax, Zmin).
- The maximum value of component S3 is determined by the z-intercept of the line passing through the point S3 (Xmin, Zmax).

Possibility-3: (along u-dir): Minimum value of component-S is more than equal to maximum value of component-T i. e. S(Xmin) >=X and S(Zmin) >=Z (Figure 2b)

Minimum and maximum values along u direction:

- The minimum value of component S1 is represented as (Xmin, Zmin).
- To determine the maximum value of component T, a line is drawn through the point S1(Xmin, Zmin) along the u direction. A perpendicular line is drawn from point T(Xmax, Zmax) to this line, and the intersection point is denoted as T'(X, Z). This point T'(X, Z) represents the maximum value of T, situated on the line passing through S1(Xmin, Zmin) along the u direction.



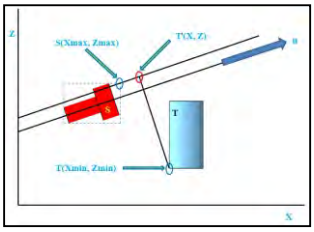


Figure 2c. S (X min) <X and S (Z min) <Z Figure 2d. S (X min) >=X and S (Z min) >=Z

Possibilities (Along u-dir) between two components in which collision may occur.

Possibility-1: Minimum value of component-S is less than maximum value of component-T i. e. S(Xmin) <X and S(Zmin) <Z (refer Figure 2c)

Minimum and maximum values along u direction:

- The minimum value of component S is represented as (Xmin, Zmin).
- To determine the maximum value of component T, a line is drawn through the point S (Xmin, Zmin) along the u direction. A perpendicular line is drawn from point T (Xmax, Zmax) to this line, and the intersection point is denoted as T'(X, Z). This point T'(X, Z) represents the maximum value of T, situated on the line passing through S (Xmin, Zmin) along the u direction.

Possibility-2: Maximum value of component-S1 is less than minimum value of component-T i. e. i. e.

S1(Xmax) <X and S1(Zmax) <Z (refer Figure 2d)

Minimum and maximum values along u direction:

- The maximum value of component S1 is represented as (Xmax, Zmax).
- To determine the minimum value of component T, a line is drawn through the point S1(Xmax, Zmax) along the u direction. A perpendicular line is drawn from point T (Xmin, Zmin) to this line, and the intersection point is denoted as T'(X, Z). This point T'(X, Z) represents the minimum value of T, situated on the line passing through S1(Xmax, Zmax) along the u direction. With this we can obtain all the limits of a component along the u-direction with change in angle Θ.

2.2.2.3. Determining the feasible/oblique direction for the rotor component in the presence of the base component:

The rotor component is incrementally rotated through angles ranging from 1 to 89 degrees. At each angle, the rotor is displaced by a unit distance, and a clash analysis is conducted. If the clash analysis results in a negative clash value, indicating interference, the rotor is promptly returned to its initial position, and the process proceeds to the next angle.

Conversely, if the clash value is found to be 0 or greater at a particular angle, it signifies that the rotor can move in that direction without encountering interference. The rotor continues its movement along this direction, ensuring that the clash value remains at 0 or greater, until the rotor's minimum value aligns with the maximum value of the base component along that specific direction. Once all clash values along a given angle are confirmed to be 0 or greater, the corresponding angle is considered a feasible/oblique direction for the rotor in the presence of the base component. Once identified, the rotor returns to its original position and ceases further movement in other directions.

After determining a feasible angle, it is recorded and stored in an angle matrix that corresponds to both the rotor and the base components. This recorded angle signifies that the rotor can be feasibly assembled in the presence of the base component at that specific angle.

2.2.2.4. Nomenclature for Direction and Angle:

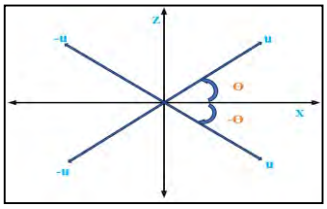


Figure 3a. Direction & Angle in plane

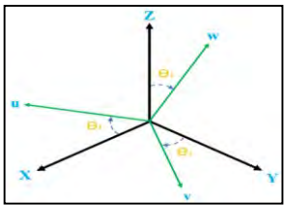


Figure 3b. Direction & Angle in 3d space

In the X-Z plane, when viewed from the positive Y-axis:

- Angle Θ1 rotation in a clockwise direction in the range of (0, π/2) is considered positive, whereas angle Θ1 rotation in an anticlockwise direction in the range of (0, -π/2) is considered negative.
- Regarding the direction 'u,' when it falls within the (x, z) quadrant, it is regarded as positive, and when it falls within the (-x, -z) quadrant, it is considered negative, all with respect to the same positive angle reference.
- Similarly, for direction 'u,' when it is situated in the (x, -z) quadrant, it is considered positive, and when it is situated in the (-x, z) quadrant, it is deemed negative, maintaining the same negative angle reference.

This convention ensures a consistent understanding of positive and negative orientations for angles and directions in the X-Z plane when viewed from the positive Y-axis. The same convention applies to angles Θ2 and Θ3, as well as directions 'v' and 'w,' in their respective (y, x) and (z, y) planes.

2.2.2.5. GFM along The Feasible/Oblique Direction of The Rotor:

The same methodology used for assessing geometric feasibility along principal directions is applied to the rotor only along feasible/oblique direction w. r. t. other components i.e. (rotor, j) where j takes other components. If the oblique direction lies within the x-z plane indicated by u-direction, a feasibility indication value 7 for positive

and value 8 for negative is assigned. If the oblique direction is within the y-x plane indicated by v-direction, a feasibility indication value 9 for positive and value 10 for negative is assigned. Likewise, if the oblique direction is within the z-y plane indicated by w-direction, a feasibility indication value 11 for positive and value 12 for negative is assigned. These values w.r.t. u, v, w directions are then incorporated and updated within the main GFM along the x, y, z principal axis respectively.

2.2.3. GFM Along Oblique Directions in 3D Space:

During the implementation of the assembly sequence generation macros for the aircraft's stub-wing, certain components have feasible/oblique directions that extend into three-dimensional space. In these cases, further investigation is necessary to account for these unique pairs of components. In this work, a GFM value of "13" is assigned to indicate that the component's feasible/ oblique direction exists in three-dimensional space (14 for negative direction). This value is then updated within the main GFM along the more suitable (visually) principal axis. This allows for the recognition and treatment of components whose assembly directions extend beyond the traditional planes. When dealing with an LV- 1 product that contains multiple parts within it, you can create a pseudo-axis system using the u, v, and w directions at a certain angle (determined visually) relative to the principal axis. This pseudo-axis system provides an alternative frame of reference for assessing assembly feasibility.

2.3. Permanent Stability Matrix Extraction (stb(3)):

The permanent stability matrix takes into account connectors like rivets, nuts, screws, and pins that connect two components. Clash analysis is performed between the connector and all other primary components to identify the two components in contact with the connector. The matrix value (i, j) is set to 3, indicating that components I and j are in permanent stability [7] (In the current methodology for LV-2, when dealing with such pairs, the base component (denoted as 'j') is determined as the one with a higher number of '1' values in the Liaison Matrix. This higher count indicates that the base component is in contact with a greater number of other components. Conversely, the other component in the pair is referred to as the appending component ('i'), which implies that component 'i' is stable with respect to component 'j', if both have same values in the Liaison Matrix then (i, j) =(j, i)=3). The code has been modified to group primary and secondary components separately, ensuring that the position of secondary components does not affect the tree diagram. The code structure has been updated based on this grouping. This method is implemented in LV-1 products and then LV-2 parts of each product.

Identification of primary and secondary components-Grouping is done based on the name of component in tree diagram

- LV-2

If the name of the component in LV-2 is any of the PIN, NUT, BOLT, SCREW, RIVET or CONNECTOR then that component is considered as secondary otherwise it is primary.

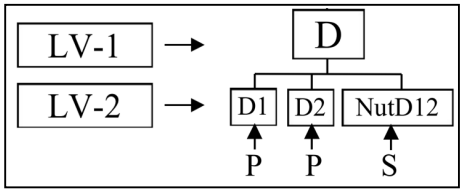


Figure 4. Primary and Secondary Components in LV-2

- LV-1

To be classified as a secondary component, an LV-1 component must meet one of the following criteria:

1. The name of the LV-1 component is one of the following: PIN, NUT, BOLT, SCREW, RIVET or CONNECTOR.
2. The names of all LV-2 components within the LV-1 subassembly are one of the following: PIN, NUT, BOLT, SCREW, RIVET or CONNECTOR.

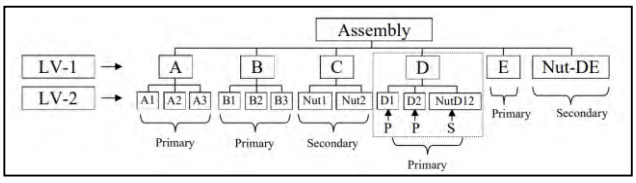


Figure 5. Primary and Secondary Components in LV-1

2.4. Part Concatenation:

Code for part concatenation is updated to work for LV-1 and LV-2 assembly.

First, assembly of two components is done, say i and j having value 1 in liaison matrix (i, j) and a value 3 in their stability matrix (j, I), indicating that these two parts are in contact with each other & component i is stable w.r.t. to component j.

When introducing a new component, denoted as 'k,' into the assembly sequence, it must satisfy specific criteria to ensure a smooth and stable assembly:
Liaison and Stability: Component 'k' should establish both liaison and stability with either 'i' or 'j,' which are the previously incorporated components in the existing sequence. In other words, one of the following conditions must hold:

- lm(I, k) = 1 and stb(k, i) = 3
- lm(j, k) = 1 and stb(k, j) = 3

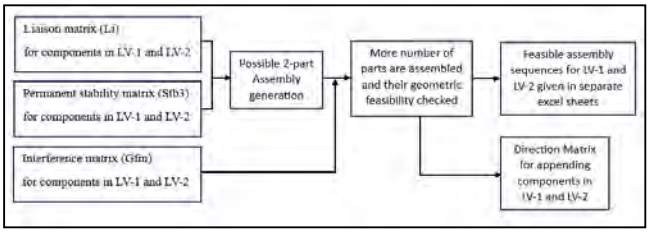


Figure 6. Part Concatenation Process

Non-Interference: Additionally, component 'k' should not interfere with any of the existing components during the assembly or disassembly process. This means that, in any one of the directional Geometric Feasibility Matrix (GFM), component 'k' should exhibit feasibility with respect to all existing components. This ensures that there are no clashes or conflicts when integrating 'k' into the existing assembly sequence [8]. The specific direction along which 'k' is feasible is recorded and added to the Directional Matrix. This process continued to add more components based on their relationships with the existing components and implemented in LV-1 products and then LV-2 parts of each product, and their ASG and Direction Matrix for appending components are exported in separate excel sheets.

3. RESULTS AND DISCUSSION

The Method as described section is implemented with the example of aircraft stub wing assembly.

3.1. Structure of aircraft stub wing-

3.1.1. LV-1 Components (Level 1):

The parts/products/sub-assemblies which directly come under the stub wing are referred to as LV-1 components.

3.1.2. LV-2 Components (Level 2):

The parts/products which come under LV-1 products/sub-assemblies are considered as LV-2 components.

oblique assembly directions.

3.1.3. Grouping of parts in LV-1 Components:

Following an examination of the stub wing, parts that can be assembled with minimum geometric conflicts with other parts are consolidated into a product. This product is categorized as LV-1. Additionally, if a single part proves to be more feasible in terms of ease geometric conflicts than a group of parts, it is also designated as LV-1. Based on the explained methodology, liaison matrix, stability matrix is generated for Level-1 and Level-2 components. Subsequently, after generating the Geometric Feasibility Matrix (GFM) for components along the principal axis, it became apparent that certain components exhibited oblique assembly directions.

Base	Rotor
3	6

Figure 7. Non-feasibility pair in LV-1

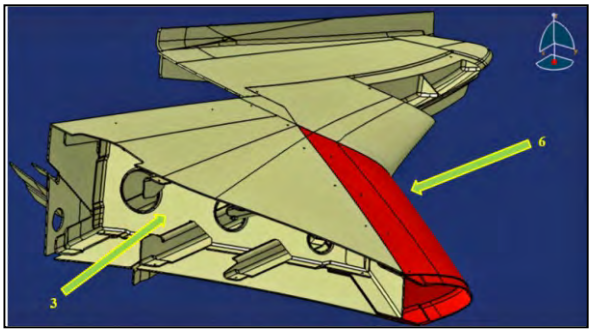


Figure 8. Component no.6 is feasible to component no.3

Table 1. Modification in GFM in Y-direction of LV-1 components due to oblique feasibility of component labelled as "Back_Panel" (component no. 6) in 3d space

Y+	Frontal	Up_surf	Middle	Low_Surf	Forw_Panel	Back_Panel	Supporter	EndPd
Frontal	0	0	0	3	0	0	0	3
Up_surf	3	0	3	3	0	0	3	3
Middle	0	0	0	0	0	0	0	3
Low_Surf	3	3	0	0	3	0	0	3
Forw_Panel	3	3	3	3	0	0	0	3
Back_Panel	3	3	0	0	0	0	3	3
Supporter	0	3	0	0	3	0	0	3
EndPd	3	0	0	0	3	0	0	0

Y+	Frontal	Up_surf	Middle	Low_Surf	Forw_Panel	Back_Panel	Supporter	EndPd
Frontal	0	0	0	3	0	0	0	3
Up_surf	3	0	3	3	0	0	3	3
Middle	0	0	0	0	0	0	0	3
Low_Surf	3	3	0	0	3	0	0	3
Forw_Panel	3	3	3	3	0	0	0	3
Back_Panel	13	13	13	0	0	0	13	13
Supporter	0	3	0	0	3	0	0	3
EndPd	3	0	0	0	3	0	0	0

In LV-2 –

Within the LV-1 product named "Middle" certain constituent parts displayed an oblique feasibility characteristic in the u, v, and w directions, which was determined through visual inspection. Oblique in u direction (1st quadrant)-

Base	Rotor
4	8

Figure 9. Non-feasibility pair in LV-2 (u direction 1st quadrant)

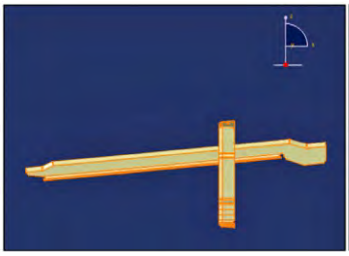


Figure 10. Feasibility in u-dir, X-Z view

Figure 11. Non feasibility of component 8 w.r.t. 4, 3d view

After visual inspection, it was determined that the part component labelled as "M8" (component no. 8) exhibited an oblique feasibility in u-direction w.r.t. part component labelled as "M4" (component no. 4). Angle of feasibility was found to be 6 degrees.

Geometric feasibility of component M8 with respect to other components was assessed along the u-direction at an angle of 6 degrees.

Table 2. Modification in GFM in X-direction of LV-2 components of sub-assembly labelled as "Middle" due to oblique feasibility of component labelled as "B2" (component no. 8) in X-Z plane

X+	M1	M2	M3	M4	M5	M6	B1	B2	B3	B4
M1	0	0	0	0	0	0	1	1	1	1
M2	1	0	0	0	1	1	0	0	0	0
M3	1	1	0	0	1	0	1	0	0	1
M4	1	1	1	0	1	0	0	0	0	0
M5	0	1	0	0	0	1	1	1	1	1
M6	0	1	0	0	1	0	1	1	1	1
B1	1	1	1	0	1	1	0	1	1	1
B2	1	1	1	6	1	1	1	0	1	1
B3	1	1	1	0	1	1	1	1	0	1
B4	1	1	1	0	1	1	1	1	1	0

X+	M1	M2	M3	M4	M5	M6	B1	B2	B3	B4
M1	0	0	0	0	0	0	1	1	1	1
M2	1	0	0	0	1	1	0	0	0	0
M3	1	1	0	0	1	0	1	0	0	1
M4	1	1	1	0	1	0	0	0	0	0
M5	0	1	0	0	0	1	1	1	1	1
M6	0	1	0	0	1	0	1	1	1	1
B1	1	1	1	0	1	1	0	1	1	1
B2	7	7	7	7	7	7	7	0	7	7
B3	1	1	1	0	1	1	1	1	0	1
B4	1	1	1	0	1	1	1	1	1	0

Oblique in u direction (-ve angle to x-axis) (4th quadrant)-

Base	Rotor
4	9

Figure 12. Non-feasibility pair in LV-2 (u direction 4th quadrant)

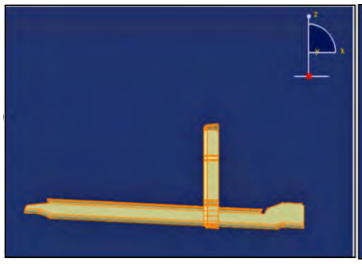


Figure 13. Feasibility in u-dir with -ve angle, X-Z view

Figure 14. Non feasibility of component 9 w.r.t. 4, 3d view

After visual inspection, it was determined that the part component labelled as "M9" (component no. 9) exhibited an oblique feasibility in u-direction with negative angle to x-axis w.r.t. part component labelled as "M4" (component no. 4)

Angle of feasibility was found to be -6 degrees. Geometric feasibility of component M9 with respect to other components was assessed along the u-direction at an angle of -6 degrees.

Table 3. Modification in GFM in X-direction of LV-2 components of sub-assembly labelled as “Middle” due to oblique feasibility of component labelled as "B3" (component no. 9) in X-Z plane

X+	M1	M2	M3	M4	M5	M6	B1	B2	B3	B4
M1	0	0	0	0	0	0	1	1	1	1
M2	1	0	0	0	1	1	0	0	0	0
M3	1	1	0	0	1	0	1	0	0	1
M4	1	1	1	0	1	0	0	0	0	0
M5	0	1	0	0	0	1	1	1	1	1
M6	0	1	0	0	1	0	1	1	1	1
B1	1	1	1	0	1	1	0	1	1	1
B2	7	7	7	7	7	7	7	0	7	7
B3	1	1	1	0	1	1	1	1	0	1
B4	1	1	1	0	1	1	1	1	1	0

X+	M1	M2	M3	M4	M5	M6	B1	B2	B3	B4
M1	0	0	0	0	0	0	1	1	1	1
M2	1	0	0	0	1	1	0	0	0	0
M3	1	1	0	0	1	0	1	0	0	1
M4	1	1	1	0	1	0	0	0	0	0
M5	0	1	0	0	0	1	1	1	1	1
M6	0	1	0	0	1	0	1	1	1	1
B1	1	1	1	0	1	1	0	1	1	1
B2	7	7	7	7	7	7	7	0	7	7
B3	7	7	7	7	7	7	7	7	0	7
B4	1	1	1	0	1	1	1	1	1	0

Oblique in -w direction (3rd quadrant)-

Base	Rotor
1	6

Figure 15. Non-feasibility pair in LV-2 (-w direction 3rd quadrant)

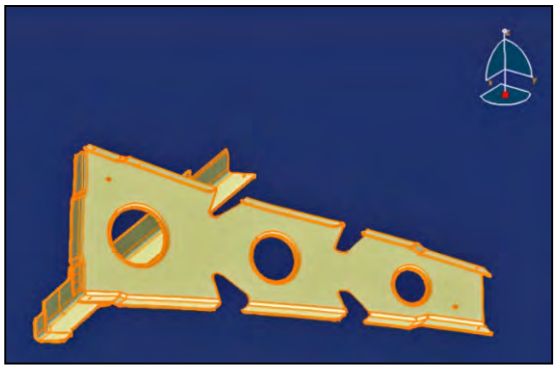


Figure 16. Feasibility in -w dir

After visual inspection, it was determined that the part component labelled as "M6" (component no. 6) exhibited an oblique feasibility in (-w) direction w.r.t. part component labelled as "M1" (component no. 1)

Angle of feasibility was found to be 3 degrees with z-axis. Geometric feasibility of component M6 with respect to other components was assessed along the -w direction at an angle of 3 degreesAngle

Table 4. Modification in GFM in Z-direction of LV-2 components of sub-assembly labelled as “Middle” due to oblique feasibility of component labelled as "M6" (component no. 6) in Z-Y plane

Z+	M1	M2	M3	M4	M5	M6	B1	B2	B3	B4
M1	0	0	5	5	0	0	5	5	5	5
M2	0	0	0	0	5	5	0	0	0	0
M3	5	0	0	5	0	0	5	0	0	5
M4	5	0	5	0	0	0	0	0	0	0
M5	5	5	5	5	0	5	5	5	5	5
M6	0	5	0	0	0	0	5	5	5	5
B1	5	0	5	0	5	5	0	5	5	5
B2	5	0	0	0	5	5	5	0	0	5
B3	5	0	0	0	5	5	5	0	0	5
B4	5	0	5	0	5	5	0	5	5	0

Z+	M1	M2	M3	M4	M5	M6	B1	B2	B3	B4
M1	0	0	5	5	0	0	5	5	5	5
M2	0	0	0	0	5	5	0	0	0	0
M3	5	0	0	5	0	0	5	0	0	5
M4	5	0	5	0	0	0	0	0	0	0
M5	5	5	5	5	0	5	5	5	5	5
M6	12	12	12	12	12	0	12	12	12	12
B1	5	0	5	0	5	5	0	5	5	5
B2	5	0	0	0	5	5	5	0	5	5
B3	5	0	0	0	5	5	5	0	0	5
B4	5	0	5	0	5	5	0	5	5	0

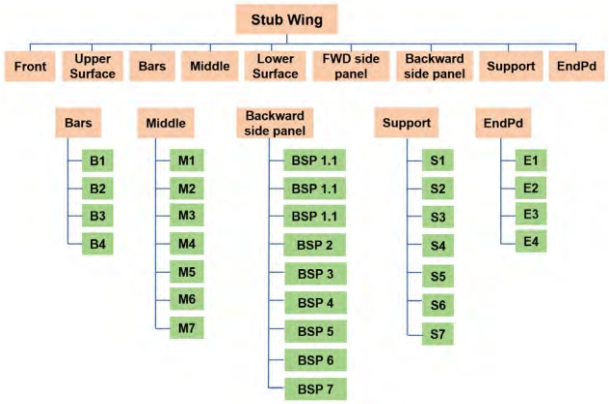


Figure 17. Tree Diagram of Stub Wing

Matrix:
The Angle Matrix is constructed based on the non-feasibility of the rotor with respect to the base. It provides information about the specific angle at which the rotor becomes feasible with respect to the base, denoted as an (rotor, base).

For LV-1 product named "Middle".

	M1	M2	M3	M4
M1				
M2				
M3				
M4				
M5				
M6	3		3	3
B1				6
B2				6
B3				-6
B4				-6

Table 5. Feasible angle of rotor(i) w.r.t. base(j)

Component Level	Base	Rotor	Plane	Direction Cosine	Angle (deg)	Oblique Direction
LV-2	1	6	z-y	[0, -wsin(3), -wcos(3)]	3	12
LV-2	3	6	z-y	[0, -wsin(3), -wcos(3)]	3	12
LV-2	4	6	z-y	[0, -wsin(3), -wcos(3)]	3	12
LV-2	4	7	x-z	[ucos(6), 0, usin(6)]	6	7
LV-2	4	8	x-z	[ucos(6), 0, usin(6)]	6	7
LV-2	4	9	x-z	[ucos(-6), 0, usin(-6)]	-6	8
LV-2	4	10	x-z	[ucos(-6), 0, usin(-6)]	-6	8
LV-1	3	6	x-y-z	[x,y,z]	-	13

Figure 18. Summary Table

Matrix Extraction for assembly “Stub_Wing”-

Liai	Frontal	Up_surf	Middle	Low_Surf	orw_Pane	Back_Pane	Supporter	EndPd
Frontal	0	1	1	0	1	0	1	0
Up_surf	1	0	1	0	1	1	0	1
Middle	1	1	0	1	1	1	0	1
Low_Surf	0	0	1	0	0	1	1	1
Forw_Panel	1	1	1	0	0	1	1	0
Back_Panel	0	1	1	1	1	0	0	0
Supporter	1	0	0	1	1	0	0	1
EndPd	0	1	1	1	0	0	1	0

X+	Frontal	Up_surf	Middle	Low_Surf	orw_Pane	Back_Pane	Supporter	EndPd
Frontal	0	1	0	0	1	0	1	0
Up_surf	1	0	0	1	1	0	1	0
Middle	1	1	0	1	1	0	1	0
Low_Surf	1	1	0	0	1	0	1	0
Forw_Panel	0	0	0	0	0	0	1	0
Back_Panel	1	0	0	0	1	0	1	1
Supporter	0	1	0	0	0	1	0	0
EndPd	1	1	0	0	1	1	0	0

Y+	Frontal	Up_surf	Middle	Low_Surf	orw_Pane	Back_Pane	Supporter	EndPd
Frontal	0	0	0	3	0	0	0	3
Up_surf	3	0	3	3	0	0	3	3
Middle	0	0	0	0	0	0	0	3
Low_Surf	3	3	0	0	3	0	0	3
Forw_Panel	3	3	3	3	0	0	0	3
Back_Panel	13	13	13	0	0	0	13	13
Supporter	0	3	0	0	3	0	0	3
EndPd	3	0	0	0	3	0	0	0

Z+	Frontal	Up_surf	Middle	Low_Surf	orw_Pane	Back_Pane	Supporter	EndPd
Frontal	0	5	0	5	0	0	5	5
Up_surf	5	0	5	5	5	5	5	5
Middle	0	0	0	5	0	0	5	0
Low_Surf	5	0	0	0	5	0	5	0
Forw_Panel	0	0	0	5	0	0	5	5
Back_Panel	5	0	0	5	0	0	5	5
Supporter	0	0	0	0	0	0	0	0
EndPd	5	0	5	5	5	5	5	0

Stb3	Frontal	Up_surf	Middle	Low_Surf	orw_Pane	Back_Pane	Supporter	EndPd
Frontal	0	0	3	0	3	0	3	0
Up_surf	0	0	3	0	0	3	0	0
Middle	3	3	0	3	3	3	0	3
Low_Surf	0	0	3	0	0	3	3	0
Forw_Panel	3	0	3	0	0	3	3	0
Back_Panel	0	3	3	3	3	0	0	0
Supporter	3	0	0	3	3	0	0	3
EndPd	0	0	3	0	0	0	3	0

Figure 19. Extracted Matrices of LV-1 for ASG

Generated assembly sequences for LV-1 components-

Table 6. First 10 aseembly sequences for LV-1 components

	228							
1	1	3	2	8	6	4	5	7
2	1	3	2	8	6	5	4	7
3	1	3	6	4	5	7	8	2
4	1	3	6	4	5	8	2	7
5	1	3	6	4	5	8	7	2
6	1	3	6	4	8	2	5	7
7	1	3	6	4	8	5	2	7
8	1	3	6	4	8	5	7	2
9	1	3	6	5	4	7	8	2
10	1	3	6	5	4	8	2	7

In assembly stub_wing total 228 possible sequences generated out of which 10 are given.

Generated assembly directions or direction matrix (DM) for LV-1 components-

For above 10 sequences their respective assembly directions (first component does not required any assembly direction)

Table 7. DM for LV-1 components for first 10 sequences

1		2	1	3	14	5	1	5
2		2	1	3	14	1	5	5
3		2	14	5	1	1	6	6
4		2	14	5	1	6	6	5
5		2	14	5	1	6	5	6
6		2	14	5	6	6	1	5
7		2	14	5	6	1	6	5
8		2	14	5	6	1	5	6
9		2	14	1	5	1	6	6
10		2	14	1	5	6	6	5

Matrix Extraction for LV-2 components of subassembly “Middle”-

Liai	M1	M2	M3	M4	M5	M6	B1	B2	B3	B4
M1	0	1	0	0	1	1	0	0	0	0
M2	1	0	1	1	0	0	1	1	0	1
M3	0	1	0	0	1	1	0	1	1	0
M4	0	1	0	0	1	1	1	1	1	1
M5	1	0	1	1	0	0	0	0	0	0
M6	1	0	1	1	0	0	0	0	0	0
B1	0	1	0	1	0	0	0	0	0	0
B2	0	1	1	1	0	0	0	0	0	0
B3	0	0	1	1	0	0	0	0	0	0
B4	0	1	0	1	0	0	0	0	0	0

X+	M1	M2	M3	M4	M5	M6	B1	B2	B3	B4
M1	0	0	0	0	0	0	1	1	1	1
M2	1	0	0	0	1	1	0	0	0	0
M3	1	1	0	0	1	0	1	0	0	1
M4	1	1	1	0	1	0	0	0	0	0
M5	0	1	0	0	0	1	1	1	1	1
M6	0	1	0	0	1	0	1	1	1	1
B1	7	7	7	7	7	7	0	7	7	7
B2	7	7	7	7	7	7	7	0	7	7
B3	7	7	7	7	7	7	7	7	0	7
B4	7	7	7	7	7	7	7	7	7	0

Y+	M1	M2	M3	M4	M5	M6	B1	B2	B3	B4
M1	0	0	3	3	0	0	3	3	3	3
M2	0	0	3	0	3	3	3	3	3	0
M3	3	0	0	3	0	0	3	0	0	3
M4	3	0	3	0	0	0	0	0	0	0
M5	0	0	0	0	0	3	3	0	3	3
M6	0	0	0	0	3	0	3	3	0	0
B1	3	0	3	0	3	3	0	3	3	3
B2	3	0	0	0	3	3	0	0	3	3
B3	3	0	3	0	3	3	3	3	0	0
B4	3	0	3	0	3	3	3	3	3	0

Z+	M1	M2	M3	M4	M5	M6	B1	B2	B3	B4
M1	0	0	5	5	0	0	5	5	5	5
M2	0	0	0	0	5	5	0	0	0	0
M3	5	0	0	5	0	0	5	0	0	5
M4	5	0	5	0	0	0	0	0	0	0
M5	5	5	5	5	0	5	5	5	5	5
M6	12	12	12	12	12	0	12	12	12	12
B1	5	0	5	0	5	5	0	5	5	5
B2	5	0	0	0	5	5	5	0	5	5
B3	5	0	0	0	5	5	5	0	0	5
B4	5	0	5	0	5	5	0	5	5	0

Stb	M1	M2	M3	M4	M5	M6	B1	B2	B3	B4
M1	0	3	0	0	3	3	0	0	0	0
M2	0	0	0	3	0	0	0	0	0	0
M3	0	3	0	0	0	0	0	0	0	0
M4	0	0	0	0	0	0	0	0	0	0
M5	3	0	3	3	0	0	0	0	0	0
M6	3	0	3	3	0	0	0	0	0	0
B1	0	3	0	3	0	0	0	0	0	0
B2	0	3	3	3	0	0	0	0	0	0
B3	0	0	3	3	0	0	0	0	0	0
B4	0	3	0	3	0	0	0	0	0	0

Figure 20. Extraced Matrices of LV-2 of product “Middle” for ASG

Generated assembly sequences for LV-2 components of sub-assembly “Middle”-

Table 8. First 10 aseembly sequences for LV-2 components of product “Middle” for ASG

	1980									
1	4	2	1	3	5	6	7	8	9	10
2	4	2	1	3	5	6	7	8	10	9
3	4	2	1	3	5	6	7	9	8	10
4	4	2	1	3	5	6	7	9	10	8
5	4	2	1	3	5	6	7	10	8	9
6	4	2	1	3	5	6	7	10	9	8
7	4	2	1	3	5	6	8	7	9	10
8	4	2	1	3	5	6	8	7	10	9
9	4	2	1	3	5	6	8	9	7	10
10	4	2	1	3	5	6	8	9	10	7

In sub-assembly “Middle” total 1980 possible sequences generated out of which 10 are given.

Generated assembly directions or direction matrix (DM) for LV-2 components of sub-assembly “Middle”-

For above 10 sequences their respective assembly directions

Table 9. DM for LV-2 components of product ‘Middle’ for first 10 sequences

1		1	1	3	6	11	8	8	8	8
2		1	1	3	6	11	8	8	8	8
3		1	1	3	6	11	8	8	8	8
4		1	1	3	6	11	8	8	8	8
5		1	1	3	6	11	8	8	8	8
6		1	1	3	6	11	8	8	8	8
7		1	1	3	6	11	8	8	8	8
8		1	1	3	6	11	8	8	8	8
9		1	1	3	6	11	8	8	8	8
10		1	1	3	6	11	8	8	8	8

Like this we get ASG and DM for other subassemblies.

4. CONCLUSION

The methodology used for feasible assembly sequence combinations has a worst-case time complexity (maximum number of possible sequences) of n! and as such, it is recommended to limit the number of components/subassemblies/ products/ parts at each level to less than say 10. This is because if the number of parts exceeds 10, the time complexity increases dramatically and becomes unfeasible. However, if there are 10 parts, the number of possible assembly sequences is 10! = 3,628,800, and the algorithm will have to evaluate over 3 million possible sequences. If the number of parts continues to increase, the time complexity becomes impractical, and it becomes difficult to evaluate all possible assembly sequences in a reasonable amount of time. After using this methodology, the assembly having more than 10 parts, we can break them down into smaller clusters of 10 or fewer parts each. By doing so, we can ensure that the time complexity remains manageable and the assembly process is still achievable. Also, in this we tried to get feasibility along oblique directions. Using the proposed algorithm considering the oblige directions and hierarchical distribution of components in different levels, the complexity of maximum number of sequences is reduced from N! (N is the total number of parts) to K x m^2 (K is the interior constant & m is the maximum number of parts in any level). The example considered here is a typical complex sub assembly of aircraft stub wing of N components (35 parts) and maximum component in a level is m (10). The number of possible sequences generated can be written as less than K x m^2 (< 20 x 10^2). However, the mathematical proof for upper bound of number feasible sequences as O (m^2) is yet to be proved.

Future Insights:

1. Present work has focused on assemblies with two levels and can be further increased to higher levels of assembly.
2. While the methodology presented in this work is applied for the typical assembly having the feasible directions along principal directions and oblique in principal planes and also in 3axes.
3. Automatic detection of oblique planes and arbitrary directions from the geometry.
4. Time complexity can be addressed while improving the algorithms

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Model Based Definition Implementation in PLM Framework for Development of Combat Aircraft

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Abstract - Model Based Definition (MBD) is the process of defining product & engineering data within a 3D CAD model. An MBD approach enables a single source of truth that is used in downstream processes in manufacturing, inspection and assembly.

Model Based Definition (MBD) is the process of using an annotated 3D CAD model that includes semantic PMI (product manufacturing information) to be the definitive authority downstream throughout the product lifecycle.

The most important benefits of MBD are the information is human-readable and machine-readable. Allowing the implementation of Smart Manufacturing / Industry 4.0 concepts. The information relies on processes data is no longer dependent on human interpretation.

The paper outlines MBD implementation within PLM Framework steps for Combat Aircraft design and development, involving pre-requisite analysis, scope definition, challenges assessment, mitigation, and effects analysis, requiring cultural changes across all levels.

This paper discusses MBD customization and configuration of PLM tools and authoring tools, focusing on 3D models as the master for downstream activities. PLM custom modules have been designed to suit MBD methodology and new methodologies have been defined to bring 2D drawing activities into 3D models. Lightweight visualization 3D PDF/SMG files are vital for downstream activities, including methods planning, tooling, manufacturing, inspection and supply chain agencies.

Keywords - Model Based Definition (MBD), PLM, Implementation, 2D drawing, MBD Model, PMI, 3D PDF/SMG and GD&T, CAA, CATIA, ENOVIA, FTA

I. INTRODUCTION

MBD, which is transforming the landscape of product development and communication in the engineering and manufacturing industries. MBD is a powerful approach that replaces traditional 2D drawings with a digital 3D model as the authoritative source of product information. MBD is a methodology where the 3D model, often created using Computer-Aided Design (CAD) software, contains all the essential information required to

manufacture and inspect the product. It includes geometric dimensioning and tolerancing (GD&T), annotations, material specifications, surface finishes, and any other necessary data. By relying on a single, authoritative 3D model, MBD eliminates the need for 2D drawings and helps streamline the product development process. The objective of this paper to share the experience of Model Based Definition (MBD) adoption for the product development, customizations required to bringing complete drawing information on to the 3D model, various process definitions for part design, assembly design and installations under PLM framework.

II. COMPLEXITY IN COMBAT AIRCRAFT DESIGN

Combat Aircraft Design involves different streams such as structural design like fuselage, wing, fin, ... and systems design for various systems like propulsion and fuel system (PFS), Hydraulics System, Environmental control system (ECS), flight control system (FCS), landing gear (LG), armaments, seat and safety, instrumentation, electrical system, avionics, etc.,

All these design group use different CAD modules like solid modelling, surface design, sheet metal, piping, tubing, composite design and electrical harness routings.

These different groups represent manufacturing information in different formats in drawings like manufacturing notes, standards, reference documents, co-ordinate tables, sectioning representation, non 3D representation with instruction, BOM tables, sketches, graphs, manufacturing notes, parts ballooning etc.

III. PREPARATION ACTIVITY MBD IMPLEMENTATION

Detailed study has been done at organization level and to identify changes required for all design groups, manufacturing groups, inspection, assembly shop floor & certification. Major steps involved in successful implementation of MBD are

- Pre-requisites requirement study across the organization to use MBD concepts
- Study on existing design creation process
- Identification of different types of data on dwg and study how to bring these data on 3D MBD models by expert team of designers and implementation team.
- Impact analysis for change in methodologies
- Infrastructure requirement analysis for design groups, methods planning, inspection & certification etc.
- Outsourcing/supply chain methodology for manufacturing activities
- Training requirement analysis with different perspective
    - MBD Data creation methodology using FTA module for design teams
    - Data consumption/visualization for methods, planning, tooling, manufacturing & assembly, inspection and other down streams groups.
- Data Security
- H/W and S/W requirements including CAD & PLM license requirements
- Light weight visualization format selection for downstream activities
- Archival process

Before implementing need to conduct in depth study of the migration from drawings to only 3D geometry models through a task team with representation from program management, all design groups along with downstream users such as methods, tooling, shopfloor, inspection, and certification agencies apart from PLM team (Implementation Team). First step was convincing all stake holders on MBD approach discussing advantages and assuring good support & handholding. Task team further discussed on feasible options and pros & cons, before concluding on representation of the data on to the MBD models.

IV. PROCESS DEFINITION FOR IMPLEMENTATION

For each step-in detail design, processes were defined and scope of implementation finalized after thorough discussions with concerned stakeholders. With focus on standardization, data redundancy and automation - customizations and interfaces at each level were identified. As part of implementation developed various modules to bring the drawing data on to MBD model ensuring

complete information and user friendliness in generating the data as well as consuming the data. Sample MBD model with PMI Information shown in Figure 1. MBD Implementation majorly focuses on

1. MBD Design Process for Part:

- Part methodology for machined parts
- Part methodology for sheet metal parts
- All system designs data – Propulsion, FCS, LG, Hydraulics, ECS, Armaments, Flight Test Instrumentation, Avionic & Electrical
- SMG /3D PDF file management process for Part
- 3D PDF file management process with standard template
- Conversion of existing models (non-MBD) to MBD models (with FTA) for aero sheet metal, machined, composite part, tubing, piping and electrical installations
- STP file management process with FTA information for Part

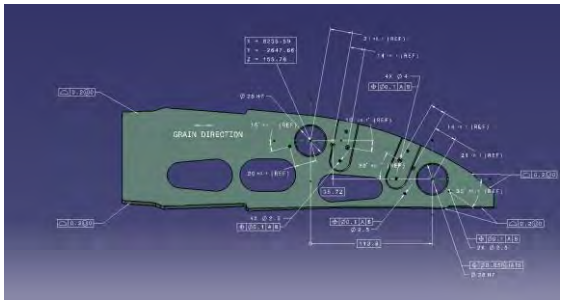


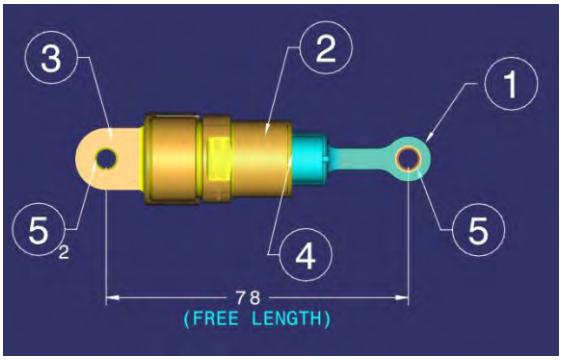
Figure 1 - Sample MBD model with PMI Information

2. MBD Design Process for Assembly:

Definition of process methodology for the following

- Assembly /Installation methodology for structural assemblies
- Methodology for various system assemblies like – Propulsion, FCS, LG, Hydraulics, ECS, Armaments, Flight Test Instrumentation, Avionic & Electrical looms & bundles with common processes to the extent possible
- SMG /3D PDF file management process for Assembly & Installation
- STP file management process with FTA information for Assembly

Sample MBD assembly show in Figure 2 & 3



2 - Spring Jack Assembly

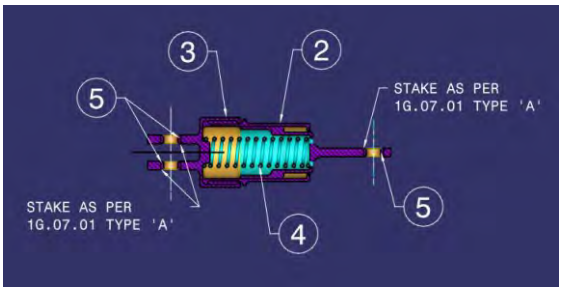


Figure 3 - Section View of Spring Jack Assembly

V. PLM & CAD TOOLS CUSTOMIZATION

Customisation in PLM and CAD allows organisation to optimise workflows, improving productivity and ensure the inhouse business requirements. The customization/integration involves combination of configuration, scripting and CAA coding for CATIA, developing codes using API's. These customizations will increase the efficiency of designers with accurate data and allows for standardization of the process.

In this implementation ENOVIA (as a PLM tool) and CATIA (as CAD tool) are utilized for detailed the customisation/integrations are as below

a) Generic Customizations:

Data model and Data Organization:

- Suitable data organization changes to manage drawings as well as 3D PDF facilitating hybrid model

Work flow customizations:

- Necessary enhancements to design workflows for MBD data release process

Standardisation:

- Start Part, Title Block templates, and other reports

Automations:

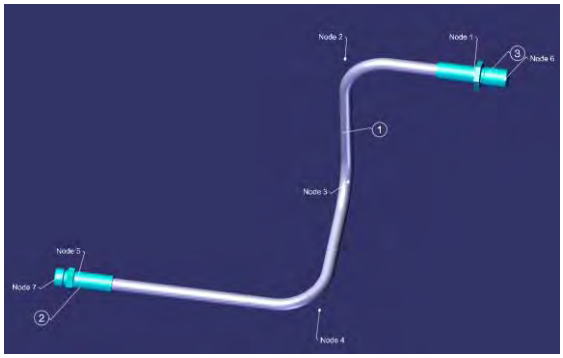
- Automatic 3D PDF/SMG generation based on maturity status in workflow
- Complete automation of title block ensuring total avoidance of any kind of manual entry
- Automatic transfer of workflow approval information on to CATPart / CATProduct for display in title block
- Release stamp insertion automation

b) Balloon Generation

Customized to bring automatic ballooning creation for parts based on item numbers in assembly.

Below Figure 4 shows hydraulics tube assembly with balloon information this automation involves customization of

A. Data flow from CATIA to ENOVIA.
B. Part item number data flowing back from ENOVIA to CATIA assembly.

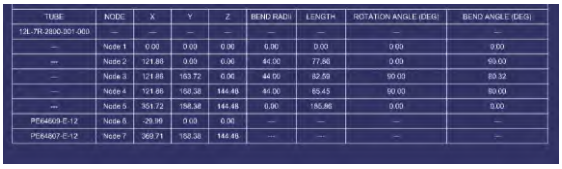


AssemblyFigure 3 - Section View of Spring Jack Assembly

c) Tube Nodes Table Co-ordinates generation (CATIA Customizations):

Automatic tube nodes information extraction and display in the form of table (Figure 5), for manufacturing and inspection requirements in MBD tube assembly. Same facility was extended to created non-tubing module Tubes/Pipes also through CAD customization, for the convenience of design groups and to make error free data.

This automation was possible on CATIA using CAA functionalities.



TUBE	NODE	X	Y	Z	BEND RADII	LENGTH	ROTATION ANGLE (DEG)	BEND ANGLE (DEG)
12L-7R-2800-001-000	—	—	—	—	—	—	—	—
—	Node 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
—	Node 2	121.86	0.00	0.00	44.00	77.86	0.00	89.00
—	Node 3	121.86	153.72	0.00	44.00	82.59	90.00	89.32
—	Node 4	121.86	158.38	144.48	44.00	65.45	90.00	89.00
—	Node 5	351.72	158.38	144.48	0.00	185.86	0.00	0.00
PE64609-E-12	Node 6	-29.99	0.00	0.00	—	—	—	—
PE64807-E-12	Node 7	369.71	158.38	144.48	—	—	—	—

Figure 5 - Tube Nodes table generation

d) Welding & Lagging representation and Automatic Weight calculation (ENOVIA / CATIA Customizations):

For wholistic design representation and DMU purposes, it was decided to represent welding and lagging in 3D. Evolved a methodology to represent welding and lagging information and also automated weight calculation for both welding and lagging, as well as filling the weight attributes for the same. This involves utilization of CAD-PLM interface for transfer of data between the two. 3D welding representation shown in Figure 6 and Lagging representation in Figure 7.

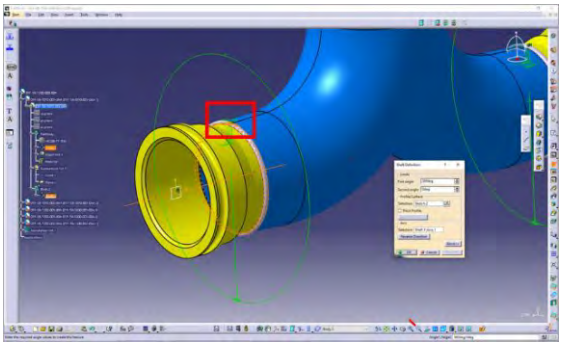


Figure 6- 3D Welding representation

Lagging representation and Automatic Weight calculation (ENOVIA / CATIA Customizations):

Figure 7 - Lagging and Insulation representation

e) Change Notice methodology - MBD:
Change Management process is essential for developmental aircraft with continuous improvement. Below is innovative way of change management implementation with colour coding required information

Different methodology developed as below

- Version management for Part with colour coding
- Version management for assembly and installations with colour coding
- Change methodology for short term changes or specific to a limited number of aircraft

The Change Notice customization involves automatic color coding for part attributes, Material attributes, all the modified notes drawing notes on MBD models, deleted notes, new notes, change in dimension and inserting revision identifier to identify the version of document. This feature improves the user convenience towards comprehending the changes in the new version of the part/assembly quickly. All the down the line stakeholders, design data consumers are benefited with this custom convenience feature. Below

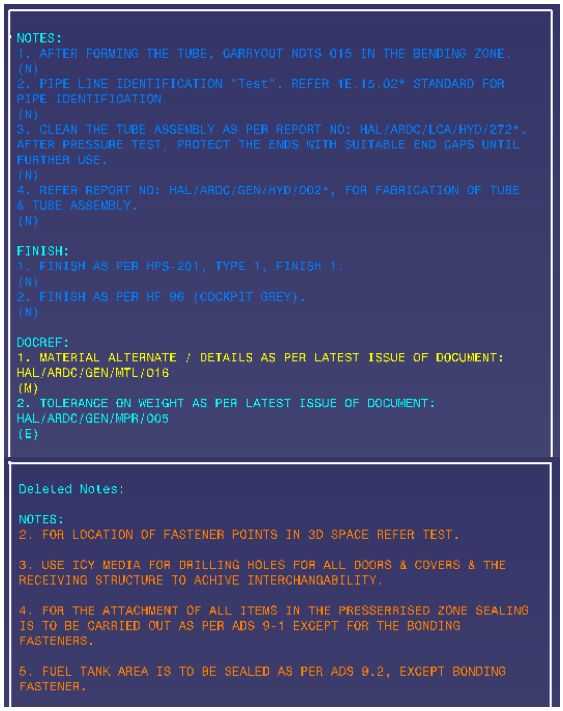


Figure 8- MBD Change Notice / Title block with Colour

Figure 8 and Figure 9 shows the change notice implemented with color coding for indicating the changes made to notes from previous version to rrent version of design document.

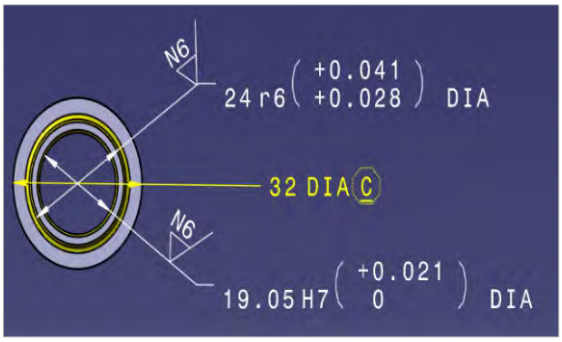


Figure 9 - MBD Change Notice / Title block with Colour

f) Automations - Electrical Harness Installation:
Electrical Harness Installation drawing creation is laborious process, time consume and required skilled man power to understand the 3D routing path in aircraft level. Figure 10 and Figure 11 representation of electrical sample loom in context with DMU.

3D MBD assembly has been automated with automatic ballooning, view generation and adding the reference designator as shown in Figure 12. This automation eliminated drawing creation and manual work with increased quality with click of a button.

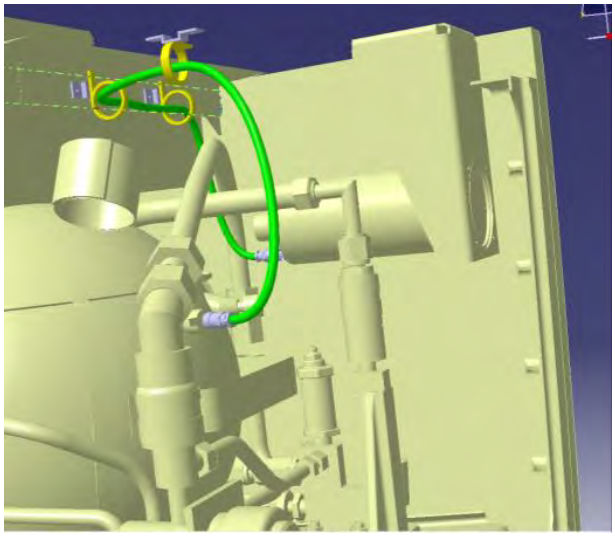


Figure 10 - Electrical Harness routing

Figure 11 - Electrical Harness routing without MBD

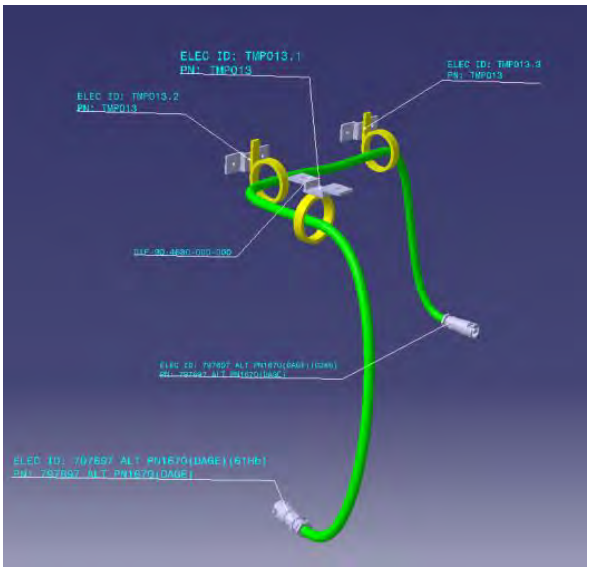


Figure 12 - Electrical Harness reference designator on 3D MBD model

g) Manufacturing Notes automation:

Automated the Manufacturing Notes, by creating centralised and standardised database integration with PLM. The notes library is customised providing flexibility to design teams to enter the variable values for some notes while keeping the text in the notes standard. This enabled the organisation level / project level standardisation of Manufacturing Notes, time saving for designers in generating notes, well organised notes make it easy for design data consumers, and made it easy to generate analysis reports with a click of a button. This automation involves customisation of ENOVIA and CATIA. Figure 13 shows below ENOVIA and CATIA interface for notes creation.

Figure 13- Manufacturing Notes management in integration with Enovia and CATIA

VI. INTEGRATION OF COMPOSER WITH ENOVIA VPM V4

Composer is tool for creating light weight CAD data creation in SMG format. To create these light weight data required multiple levels of customisations.

- Customization of CATIA Composer profile to create views directly from captures.
- Automate extraction of attributes and its value to publish in the title block in MBD model.
- Implemented batch process generation and management of the lightweight visualization format in ENOVIA VPM.
- Taken care the synchronization process when files get modified in workflow/ work in process files
- · 3D PDF/SMG visualization solution for parts/assembly/installation from Enovia-VPM

VII. ENHANCEMENT WITH OTHER TOOLS

Q - Checker is a tool to check the quality of the CAD data. Need to enhance the Q-Checker tool to identify & handle MBD models. In this context added new profiles with additional MBD check & rules.

VIII. METHODOLOGY FOR DATA SHARING TO SUPPLIER

Sharing data with vendors for manufacturing activities is a common practice in aircraft industry. It allows companies to collaborate with their suppliers, ensuring the production of high-quality products and efficient supply chain management. Outsourcing manufacturing activity allows companies to utilise their resources and efforts on innovation, design and system integration. It facilitates increase in rate of production without compromising the quality. However, it is essential to handle data sharing with vendors carefully to protect sensitive information and maintain security and compliance.

Evolved the methodology to share the data with the vendors, light weight format which is converted by inbuilt filters to avoid export of intellectual data into STEP and light weight model files.

IX. CHALLENGES ASSOCIATED WITH MBD ADOPTION

1. Cultural Resistance: One of the significant challenges in implementing MBD in the aerospace industry is to bring in the necessary cultural change. Traditional engineering and manufacturing practices often rely on paper-based drawings and documents. For designers, to work with models and bring in all manufacturing info on to model without using drawings is a major change in working and hence resistance to change is inevitable. For various down the line design consumers like methods planning, manufacturing, inspection & certification, etc., departments traditionally used to work with drawings, will find it difficult to work without drawings.

2. Skill and Training: MBD requires a different set of skills and tools compared to traditional 2D drawings. Employees need to upgrade their skills through trainings and practice in using 3D modeling software, interpret model-based information, and understand the associated standards and guidelines (e.g., ASME Y14.41).

3. Interoperability: The aerospace industry often involves multiple stakeholders and software tools throughout the product lifecycle. Ensuring interoperability and data exchange between various software platforms, such as CAD, CAM, and PLM systems, can be complex need to be taken care of all the tools exist in product development lifecycle.

4. Standards Compliance: Adhering to industry-specific standards and regulations is crucial in aerospace manufacturing. MBD standards, such as ASME Y14.41 and ISO 16792, must be followed accurately. In this project ASME Y14.41 modified to suit internal requirements.

5. Data Security: Aerospace companies deal with sensitive and classified information. Implementing MBD means managing and securing digital data effectively. Ensuring data security and preventing unauthorized access or data breaches is a critical concern.

6. Cost of Technology: Investing in the necessary software, hardware, and infrastructure for MBD implementation can be expensive. Small and medium-sized aerospace companies may find it challenging to allocate the budget required for this transformation. Dealing with small scale and medium scale manufacturing organisations can be a challenge.

Long-time data archival:

7. Supplier Integration: Aerospace manufacturers often work with a network of suppliers and subcontractors. Coordinating MBD processes with these external partners, some of whom may still rely on traditional methods, can be a logistical challenge.

8. Quality Assurance: Ensuring the accuracy of MBD data and models is essential for aerospace safety and quality. Implementing robust quality control and validation processes for MBD can be resource-intensive. In this project enhanced Q-Checker rules to suit MBD process was implemented.

9. Certification Approval: Aerospace products require regulatory approval from agencies con-

vincing these agencies of the safety and effectiveness of MBD processes may require additional effort and documentation.

Challenges and Considerations for MBD Implementation:

- Cultural change management and workforce training
- Standards and industry compliance
- Interoperability issues and data exchange
- Integration with legacy systems and suppliers

X. ACCOMPLISHMENTS

Model Based Definition (MBD) is more than just a buzzword, it's a paradigm shift that is change in the design and manufacturing streams culture. Which will bring numerous improved benefits and achievements.

1. Faster in Design Cycle:

With MBD, design iterations becomes faster and more efficient. Modifying the 3D model allows engineers to evaluate different design possibilities without the need to manually update multiple 2D drawings. As design and manufacturing information of part/product in one file, these MBD models are completely synchronised.

2. Collaboration:

It not only streamlines engineering and manufacturing processes but also improves collaboration, reduces errors, and enhances overall product quality

3. Re-use of data:

Picture the future state of a company using Model Based Definition with benefits such as creating reusable components instead of recreation. Effort in re-creating the drawings drastically reduces

4. Cost reductions:

Benefits of Model Based Definition is Cost reduction, due to the fact that no 2D drawings need to be generated. Reduction in scrap and rework, due to misinterpretation of information from the 2D drawings.

5. User friendly of design:

2D models, which can be difficult to interpret and visualize, MBD enables stakeholders to better understand the design intent and product specifications. As the models are accessible to all the levels, imagination of real product from 2D drawing is eliminated and reduces wrong assumption of the product and able to take more informed decisions within every area of the organization including engineering, manufacturing, marketing, operations, or purchasing

XI. CONCLUSIONS

Model Based Definition is revolutionizing product development and communication by replacing traditional 2D drawings with a comprehensive 3D model. Its benefits include improved communication, reduced errors, enhanced collaboration, and cost savings. Although MBD implementation might present challenges, the advantages it offers make it a transformative approach for modern engineering and manufacturing.

Model Based Definition aligns well with the principles of Industry 4.0, the fourth industrial revolution focusing on automation, data exchange and smart manufacturing. MBD enables seamless data exchange between different stages of the product lifecycle, supporting digital twin concepts and advanced manufacturing processes.

MBD Implementation achieved through deployment of suitable tools, customising to suite the requirement of single source of truth, avoiding repetitive task, automating manual process ensuring effective data capture of all levels in design cycles in PLM environment with complete traceability.

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Towards Seamless Collaboration in Aerospace Analysis: The SMARaN System Implementation

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Abstract - Aerospace structural design and development encompass a variety of simulation processes and handling of extensive data by multiple analysis verticals, which are intricately interdependent. However, analysis teams often tend to operate in isolation, leading to data redundancy, duplication and variations in results due to the use of different analysis models. Additionally, the current system lacks comprehensive tracking of the analysis process followed by each team.

To address these challenges, we introduce SMARaN (Simulate, Manage, Automate, Record, and Network), a simulation process and data management system. SMARaN streamlines the analysis procedures of each group, facilitates efficient data handling, storage and transfer between teams, and ensures proper tracking to meet project timelines. The system optimizes procedures from pre-processing to solving and postprocessing, leveraging MATLAB and Python scripts or in-house codes for automation.

Notably, SMARaN establishes a crucial link between the analysis data and the Product Lifecycle Management (PLM) environment, enhancing traceability and simplifying drawing releases. In the initial implementation stage, SMARaN is utilized to handle the process and data for loads, stress, and dynamics analysis teams, specifically focused on combat aircraft structural design.

As we progress, our ultimate goal is to expand SMARaN to encompass all analysis verticals, including fatigue, materials, and aeroservo-elasticity, as well as testing procedures and test data management. Our vision is to create a digital twin for each tail number of the aircraft, further enhancing efficiency and precision in aerospace structural design and development.

Keywords - SMARaN, SLM, Simulation Management, Data Management, Process Management, Knowledge Management

I. INTRODUCTION

In the 120 years since the Wright Brothers' historic flight, the aviation industry has undergone profound transformations, propelled by advancements in technology and data management. The advent of computers, CAD (ComputerAided Design) software, and simulation tools has led to an exponential increase in the volume of generated and stored data. While Product Lifecycle Management (PLM) systems adeptly handle CAD-related data and processes, the management of data and processes within the simulation environment lags behind.

Today's aircraft design landscape demands a multitude of analyses to ensure occupant safety and structural integrity under diverse loads and conditions. Many of these analyses share common elements and rely on repetitive data. Modern simulations produce vast datasets, often reaching tens to hundreds of gigabytes per iteration. Effectively managing and organizing data of such magnitude, even with advanced storage systems, presents unprecedented challenges.

This work is driven by the imperative to enhance the analysis processes within individual groups operating in the aircraft design industry. The primary objectives are to boost productivity,

centralize data storage, ensure traceability, and eliminate data redundancy. The ultimate goal is to create a refined finite element model for each aircraft tail number, encompassing all modifications, material replacements and anomalies that occur throughout the aircraft's lifecycle. This will enable highly accurate predictions and results.

However, the implementation of this ambitious initiative is not without its challenges:
Data: Data was previously managed in isolated silos by each group, lacking interoperability and leading to data duplication and ambiguity. Manual naming systems were used, which lacked traceability and a common data model.

Process: There was no documented process followed by each group who rather followed best practices, resulting in issues such as software selection, version control and manual file uploads. A step-by-step approach to capturing and automating these processes for each group is essential.

Execution: Organizing data in a tree structure for traceability and addressing challenges associated with remote execution and data transfer from High-Performance Computing (HPC) systems were significant hurdles that needed to be overcome.

This paper explores these challenges and the solutions devised to streamline aerospace analysis in detail.

II. LITERATURE REVIEW

The transformative potential of collaborative simulation methodologies has been recognized by scholars in the field. One exemplary study by Gagan Syal, detailed in his PhD thesis [1], delved into continuous product validation processes based on networks of diverse digital simulation methods. His research, primarily conducted in the automotive industry, highlighted the benefits of interconnecting simulation methods. This approach not only improved the quality of Computer Aided Engineering (CAE) results but also reduced the dependence on hardware prototypes. Moreover, it fostered enhanced team collaboration and optimized existing processes, as exemplified by the incorporation of CAEProNet.

Similarly, Gaetan Blondet et al. explored Simulation Data Management and adaptive design of experiments in their paper [2]. By examining possible connections between these domains, they uncovered opportunities for streamlining simulation processes. Blondet and his team identified the pressing need for novel methodologies capable of efficiently managing the escalating influx of data. Their research is pivotal in addressing the challenge of mitigating computational costs associated with numerical design experiments.

In line with these studies, the CIMdata report on Simulation Lifecycle Management (SLM) sheds light on advanced product suites, as exemplified by Dassault Systemes Simulia SLM [3]. The report emphasizes the role of these suites in enhancing collaboration, repeatability and auditability in simulation workflows. Notably, it highlights that the full potential of simulations often goes unrealized due to disconnected and ineffective practices within the broader product development ecosystem.

Collectively, these scholarly works underscore the significance of seamless collaboration and effective data management in simulation-driven industries, aligning closely with the goals and objectives of the SMARaN system.

III. SMARAN SYSTEM

A. SMARaN - Streamlining Aircraft Analysis Through Advanced Networking

The SMARaN system, an acronym for Simulate, Manage, Automate, Record, and Network, is a pioneering framework and platform engineered to foster seamless collaboration among diverse analysis groups within the aircraft design and simulation domain. Its core objectives encompass process optimization, efficient software tool utilization, harnessing high-performance computing (HPC), centralized data management,

and task automation. The overarching aim is to significantly reduce turnaround time, enhance productivity, and elevate the quality of aircraft design and simulation processes.

B. Selecting the Optimal Framework

In an extensive evaluation process, various off-the-shelf frameworks, including Dassault Systemes 3D Experience, MSC SimManager, and Siemens SIMCENTRE, underwent rigorous scrutiny. Each framework addressed real-world problems and was meticulously assessed using a comprehensive evaluation matrix encompassing vital specifications. Following this evaluation, the Dassault Systemes 3D Experience platform emerged as the ideal foundation for implementing the SMARaN system. A typical evaluation matrix used to evaluate each of the vendor is shown in Table 1.

C. Structured Workflow via Web-Based Interface

SMARaN features an intuitive web-based interface that seamlessly connects with the SMARaN server. The core of this interface lies in pre-defined process templates. These templates serve as blueprints, capturing the distinctive process flows of specific analysis groups during various analytical activities. Engineers are guided through tasks with precision, ensuring adherence to predefined sequences. Additionally, the system seamlessly integrates a spectrum of simulation packages, further enhancing its usability and versatility.

D. Initial Focus: Critical Disciplines

In its initial phase, SMARaN concentrates on three critical disciplines: Aircraft Loads Analysis, Stress Analysis and Dynamics Analysis. The journey commences with the execution of a Global Finite Element Analysis for a complete combat aircraft. This includes the entire process from Global Finite Element Mesh generation to intricate tasks such as mapping of aerodynamic loads, static aeroelasticity, and flutter computations. Notably, SMARaN simplifies the transfer of mesh and load data between the Stress Analysis team and the Loads and Dynamics team, fostering enhanced traceability and efficiency.

TABLE I. EVALUATION MATRIX

Sl. No.	Criteria	Score
01	Work procedure definition	
02	GUI of SPDM Environment	
03	Ease of usability / customization	
04	Execution of process on stand-alone machine	
05	Execution of process on HPC	
06	PLM to SPDM connectivity and data transfer	
07	SPDM to PLM connectivity	
07	Assigning roles and access	
08	Allocation of work (manager to engineer)	
10	Pre-processor connectivity (Hypermesh)	
11	Import of Aerodata	
02	Matlab tool connectivity and launch	
13	Import of GFEM from Server	
14	Model summary of imported GFEM	
15	Manager check and approval (automatic)	
16	Patran (FLDS) connectivity and launch	
17	Nastran connectivity and launch	
18	Excel connectivity and data population	
19	Data reuse	
20	Summary of results	
21	Dashboard for automation	
22	Comparison of results	
23	Report generation	
24	Centralized storage	
25	Audit trail and data retrieval using tree	

E. Key Objectives of SMARaN

SMARaN system is designed to achieve several key objectives:

Data Management: The system provides a configurable platform for managing data from diverse CAE applications and in-house tools. It facilitates mapping between CAD models and simplified CAD models, supports simulation data reuse, and automatically records and displays the complete Audit Trail and Pedigree. Additionally, it empowers Variant Management and Model revision management.

Parameter Management: SMARaN offers automated parameter metadata population for CAE models and results. It logically groups key parameters, enables efficient parameterbased searches, and supports the comparison of simulation analysis and its parameters.

Process Management: The system comprehensively supports the entire workflow, from project initiation to report generation. It ensures meticulous tracking and auditing of CAE lifecycle activities, integrates seamlessly with various analysis software, and automates tasks through batch or script execution. Engineers can create a library of workflow processes and benefit from a checklist and approval system.

Knowledge Management: SMARaN promotes best practices and enforces consistent process and resource usage. It allows for the retention and reuse of valuable simulation Intellectual Property (IP) and facilitates the sharing of expert knowledge in a reusable format.

Execution Management: Engineers can submit and execute jobs on local, remote (cluster), or high-performance computing machines. The system optimizes hardware and software resource utilization and provides comprehensive execution monitoring through a unified dashboard.

Enterprise Management: SMARaN enables the seamless integration of simulation processes into enterprise projects and Product Lifecycle Management (PLM) and Product Data Management (PDM) systems.

Data Security: The system ensures data security through granular permissions at both the global and individual model levels. It integrates with standard authentication protocols, including Lightweight Directory Access Protocol (LDAP), Active Directory, and XML-based authorization.

Architecture: SMARaN boasts an open architecture that is easily configurable for various CAE and non-CAE applications or tools. It is accessible through web browsers, scalable, and supports multiple instances of web servers with load balancing.

Visualization: The system supports 3D visual collaboration tools such as VCollab and JT for web-based CAE data viewing and data reduction.

In summary, the SMARaN system represents a transformative leap in the aircraft design and simulation domain. Its holistic approach to data and process management, coupled with seamless integration and automation, promises to revolutionize the industry, fostering enhanced collaboration, efficiency, and ultimately, safer and more advanced aircraft design.

IV. METHODOLOGY

A. Enhancing Collaboration and Efficiency

In the existing system, individual analysis groups operate in relative isolation, maintaining their data in distinct storage locations or on local machines. This isolation often leads to data loss due to system crashes, a lack of traceability and the duplication of data. Moreover, many analysis groups employ similar simulation models, with slight variations. Consequently, the exchange of data between these groups, often reliant on physical media or email, introduces challenges related to traceability and timeline management. Additionally, each group employs unique approaches to simulation tasks, necessitating extended training periods for new team members, even if they have undergone specific tool training.

B. Streamlining Processes

To address these challenges, the SMARaN system streamlines processes, centralizes data storage, and facilitates data exchange. It accomplishes this by capturing the simulation procedures of each analysis group and transforming them into structured workflows, ensuring repeatability. These workflows are further translated into process templates within the framework, rigorously validated by analysis teams. This comprehensive approach spans multiple steps, from extracting geometry from PLM environments such as Enovia VPM or Teamcenter to Manager-to-Engineer work allocation and sub-assignments. These templates encompass both pre and post-processing stages, utilizing a variety of tools, including MSC Nastran, Patran, Altair Hyperworks, Catia V5, as well as custom scripts in MATLAB and Python. Users are empowered to select specific tool versions, and when applicable, leverage HighPerformance Computing (HPC) resources available within the organization.

C. Creating a Comprehensive Input Database

The initial phase of the process involves generating an input database that serves as the foundation for subsequent simulations. This comprehensive database draws from shared input data derived from various groups, departments, or external organizations. It encompasses structural and aerodynamic mesh data, along with associated information such as aerodynamic load data and mass data. To ensure meticulous traceability and dependency tracking, a structured tree arrangement is adopted.

D. Verification and Automation

Once the input database is established, the next critical step is data verification and manual computations. After conducting a manual computation iteration, the system automates subsequent tasks using the same input files, facilitating the study of multiple configurations. This automation extends to post-processing activities, which are streamlined through the implementation of MATLAB and Python programs. These automated processes significantly reduce processing time, enhance data consistency, and minimize the scope for human error.

The SMARaN system's methodology thus not only addresses existing challenges but also optimizes collaboration, data management, and computational efficiency within the aircraft design and simulation environment.

V. CASE STUDY: LOAD COMPUTATION IN COMBAT AIRCRAFT STRUCTURAL DESIGN

In the realm of load computation for combat aircraft structural design, the cornerstone of the process is the creation of an input database housing critical data components:

Global Finite Element Model (GFEM) sourced from the stress analysis team.

Station-wise Mass distribution data provided by the mass and CG team.
Aerodynamic pressure distribution furnished by the aerodynamic team.

Rigid and Flexible aerodynamic mesh, meticulously crafted by the loads team.

Rigid and Flexible splines, strategically bridging the aerodynamic mesh with the structural GFEM.
Monitor points (MONSETS), meticulously placed to capture bending moment, torsion moment, and reaction forces at key attachments.

A typical loads workflow is shown in Fig 1.

The iteration commences with the manager's selection of a specific aircraft configuration for a new cycle, entrusting the task to the designated engineer. The engineer, in turn, delegates the task to their team. Initial preparations revolve around the creation of a Rigid aerodynamic mesh, which is then handed over to the aerodynamics team for the crucial task of load mapping. The mapped aerodynamic loads, spanning alpha, beta, Angle of Attack (AoA), Angle of side slip (AOSS) combinations, and control surface deflections, constitute pivotal input data for the load computation phase. This iterative process ensures

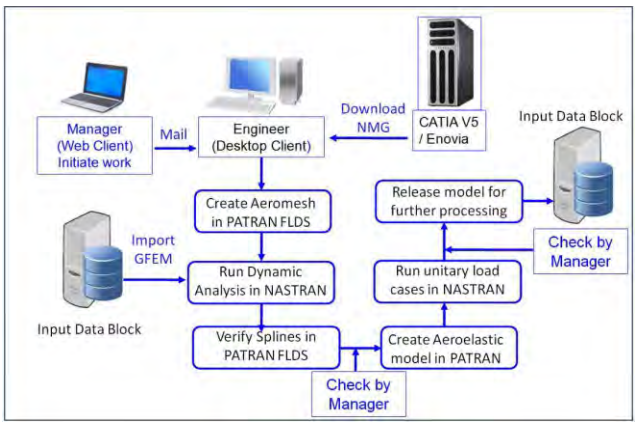

Fig 1. A typical loads computation workflow

minimal loss of load data, typically below 5%, when transitioning from a finely detailed CFD mesh to a coarser Rigid Aerodynamic mesh.

The aerodynamic load data, represented as nodal pressure (cp), is subjected to transformation into nodal force data. This transformation is achieved through the synergy of MSC Nastran and proprietary MATLAB codes. The resultant force data then serve as essential include files for the ensuing rigid analysis.

To ensure seamless interpolation of aerodynamic loads between the rigid aerodynamic mesh and the structural GFEM, the loads team generates rigid splines. Prior to commencing load computations, the integrity of the GFEM is scrutinized, with a focus on continuity and mode shape verification. The incorporation of station-wise mass distribution is likewise subjected to rigorous validation through modal analysis, specifically SOL 103 in Nastran. This comprehensive verification process guarantees the precision of spline interpolation.

The rigid analysis phase integrates the aerodynamic load data, rigid aerodynamic mesh, GFEM, rigid splines, and mass data. This computational run yields essential displacements, subsequently employed as input for the flexible run computations. The flexible run mirrors the GFEM employed in the rigid analysis, supplemented by mass data, a flexible aerodynamic mesh, corresponding splines, and output data from the preceding rigid run.

The flexible run serves a pivotal role in restoring displacements to the aerodynamic mesh and calculating differential pressure (Δcp) resulting from the deflection of lifting surfaces. The cumulative pressure differentials are harnessed to compute unitary cases, which are then amalgamated to derive various maneuver cases for aircraft stress analysis.

The initial iteration closely parallels a manual process, resembling traditional non-SMARaN methods. However, once manual verification of the aerodynamic mesh, splines, and monitor points is completed, the SMARaN system seamlessly transitions to automated computations. These automated processes are adept at handling distinct altitudemach number combinations without necessitating manual intervention.

Moreover, the SMARaN system goes beyond merely automating computations; it extends its reach to postprocessing tasks as well. Here, outcomes from multiple iterations are synthesized to generate comparative plots. This post-processing automation harnesses the power of MATLAB and Python scripts to extract and tabulate data pertaining to reaction forces and actuator forces. The result is a substantial reduction in processing time, a decreased margin for manual errors, and an overall enhancement of efficiency within the load computation process.

VI. EXPANDING SMARAN FOR COMPREHENSIVE ANALYSIS

In alignment with the methodology described in Section 5, the scope of SMARaN has been broadened to encompass not only load computation but also the domains of flutter, dynamics, and stress analysis. Within each of these specialized teams, unique workflows leveraging a range of software tools have been diligently translated into structured processes and seamlessly integrated into the versatile SMARaN framework.

The stress analysis team, responsible for a spectrum of analyses including component-level

scrutiny, GFEM-level investigations, as well as both preliminary and detailed analyses, has seen its diverse processes intricately woven into the fabric of the SMARaN environment. Similarly, the dynamics and flutter analysis teams mirror the workflow employed in load computation for global aircraft models. Additionally, these teams have developed specialized workflows tailored for localized dynamic analyses.

In pursuit of broader horizons, the vision for SMARaN extends to the integration of other vital disciplines. This envisioned expansion would encompass fatigue analysis, material science investigations, and the complex domain of aeroservoelasticity. Such a comprehensive integration promises to harmonize and streamline the various analysis disciplines inherent to the intricate airframe structures of an aircraft. Furthermore, it contemplates the inclusion of component-level testing, extensive ground testing, and even in-flight aircraft-level tests, contributing to the continuous enhancement and fine-tuning of analysis procedures.

At the pinnacle of its aspiration, SMARaN envisions the creation of a digital twin for each aircraft, intimately linked to its corresponding tail number. This digital twin, a holistic representation, would encapsulate intricate details of the aircraft's lifecycle. It would diligently record technical anomalies, material substitutions, and aircraft-level modifications. This visionary digital twin holds the promise of significantly elevating the fidelity of simulations, facilitating a closer alignment with the actual behaviour of the aircraft. The ultimate goal is to provide a comprehensive and highly accurate tool for understanding, predicting, and optimizing aircraft performance throughout its operational life.

VII. DISCUSSION

A. Achievements and Ongoing Development

The successful implementation of the SMARaN framework within the aircraft load computation workflow marks a significant milestone. Currently in the final stages of testing for the stress and dynamics workflows, SMARaN has already demonstrated its potential to improve operational efficiency and data management.

In the domain of aircraft load computation, SMARaN has streamlined processes by introducing automation for configuration studies and post-processing. This not only accelerates the pace of work but also enhances the overall efficiency of the workflow. A notable achievement is the centralization of data storage, which simplifies tracking and sharing, thereby mitigating issues associated with data management and fostering greater collaboration among analysis groups.

B. Overcoming Implementation Challenges

The journey of implementing SMARaN was not without its challenges. Handling data, managing processes, and executing tasks presented formidable obstacles. However, these challenges were effectively surmounted through a collaborative approach involving close interactions with endusers and multiple iterations. This cooperative strategy was instrumental in tailoring the system to meet the specific needs and nuances of the aircraft design and simulation environment.

C. Expanding Potential

Looking ahead, the potential for SMARaN is substantial. While it has already made significant strides in enhancing the load computation workflow, its application can be extended to encompass the entire spectrum of simulation activities related to airframe design for combat aircraft. Such a holistic integration has the potential to lead to further gains in productivity, efficiency, and collaboration.

The ultimate vision for SMARaN, as outlined in Section 6, is ambitious and forward-thinking. The concept of creating digital twins for each aircraft, complete with detailed records of modifications, technical issues, and material replacements, represents a cutting-edge approach to simulation and analysis in the aviation industry. This vision holds the promise of not only improving design processes but also providing a powerful tool for

ongoing maintenance and optimization throughout an aircraft's operational life.

In conclusion, SMARaN has emerged as a valuable asset in the realm of aircraft design and simulation. Its successful implementation in load computation and its ongoing development for other critical workflows underscore its potential to revolutionize the way analysis groups collaborate and manage data. With careful refinement and continued integration, SMARaN has the capacity to play a pivotal role in shaping the future of aircraft design and simulation.

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Implementation of an MPC-based Closed Loop Trajectory Planning and Trajectory Tracking Approach in a Discrete Virtual Environment

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Abstract - This work proposes a novel implementational scheme for a Model Predictive Control based approach for performing several on-road vehicle maneuvers in a level 4 autonomous vehicle on a commercial simulation test bench. This scheme for implementing Model Predictive Control ensures improved trajectory tracking performance and reduced effort on tuning the governing parameters as compared to a classical PID controller used for the same purpose. Moreover, this implementation works in a discrete-time environment using a generalized vehicle dynamical model for the prediction step in the MPC. This enables the creation of scalable simulation framework the functioning of which, is coherent with a real-world vehicle control unit (VCU) implementing control algorithms while inducing vehicle-independent and maneuver-independent functioning of the algorithm. The results of these MPC simulations are consistent with the EURO-NCAP 2020 protocol designed for benchmarking Autonomous Vehicle performances in simulation and real worlds (Euro NCAP).

Keywords - Modeling and Simulations, MPC, Optimization, Discrete-time Control, Motion Planning

I. INTRODUCTION

Scenario based testing has become a leading solution to help car manufacturers prove the safety and robustness of automated driving systems and comply with the regulatory procedures defined by homologation bodies like Euro NCAP. In virtual environments, these procedures are recreated with static (roads) and dynamic actors (vehicles, pedestrians, cyclists). To follow the paths defined in these procedures, a 'virtual driver', which is basically a type of controller, is required that helps the vehicle to navigate such paths. With stringent constraints defined by regulatory standards on the controller performance, researchers are motivated to explore multiple methods for path planning and trajectory tracking. One such driver is a PID based controller which, with tuned gains, helps the vehicle to follow a given trajectory. This controller is hence restricted to the vehicle and maneuver

specifications and as a result cannot be scaled to diverse types of road environments and maneuvers. Different approaches have been examined including geometric as well as optimal control techniques, to find a scalable controller that is independent of vehicle and maneuver constraints. Most popular geometric controllers are Pure Pursuit and Stanley. These are based upon the concept of reducing path offset and heading error. As a result, these use only vehicle kinematics to track a given path assuming no slip between tire and road. This makes these geometric controllers best suited for traffic vehicles (or kinematic models) and for low-speed dynamic vehicles with dedicated state of tuned parameters to minimize offset and heading error.

In this work, we show the implementation of a Model-Predictive Control based approach to ensure trajectory tracking and test this approach in a discrete virtual environment of SCANeR with a black box vehicle dynamic model. With the proposed architecture, the reference trajectory is generated onthe-go for every maneuver depending on the road dimensions and real-time vehicle data received from the simulator. It includes the reference or ideal set of points which we would like our vehicle to follow and the data for each point corresponds to the entire state of the vehicle [$x^{\cdot}$ $y^{\cdot}$ w w x $y^{\cdot}$] which denote the following: $x^{\cdot}$ – longitudinal velocity (vehicle frame), $y^{\cdot}$ – lateral velocity (vehicle frame), $w^{\cdot}$ – vehicle yaw rate, w – vehicle yaw (global frame), x – vehicle x co-ordinate (global frame), y – vehicle y co-ordinate (global frame). This implementation has been inspired from [5] where a similar objective was achieved, however, in a continuous environment. We build upon this work to improve performance and make the controller robust to disturbances, generic with respect to dynamic vehicle models and independent of maneuvers.

II. CONTROLLER FUNCTIONING

A. Controller Architecture

In this section we elaborate upon the detailed implementation architecture for the MPC-based controller and also compare it with a PID-based control architecture. These architectures have been deployed in MATLAB-Simulink along with APIs used for communicating data with SCANeR's virtual environment. Fig. 1 shows the PID-based control architecture. Based on the desired maneuver, a reference path is decided which would be followed by the vehicle in order to successfully complete the maneuver within stipulated tolerances about the reference path. Along with the reference path, a reference velocity, and acceleration in each Cartesian directions is also decided. These reference values are decided based on NCAP's safety requirements and regulations, to which an autonomous vehicle's performance must adhere to. Fig. 1 shows the implementation of the lateral drifting maneuver (necessary for LSS testing). From the virtual environment, we acquire data about the vehicle's road gap (from the lane center), the curvature and heading for the road and the vehicle data including - longitudinal and lateral velocities, acceleration and position of the vehicle on the road (in global and Frenet co-ordinate systems). Based on the maneuver, the NCAP data is a pre-defined set of position, road gap, velocity, acceleration values which are sent to the controller as reference values. **Note** - Road gap is a special parameter needed to be monitored specifically for lateral drifting maneuver since the rate of change of the road gap with respect to the lane center is the lateral velocity of the vehicle. A simple PID

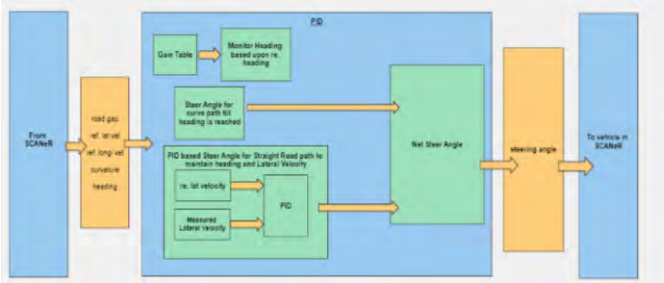


Fig. 1. PID-based controller architecture for LSS

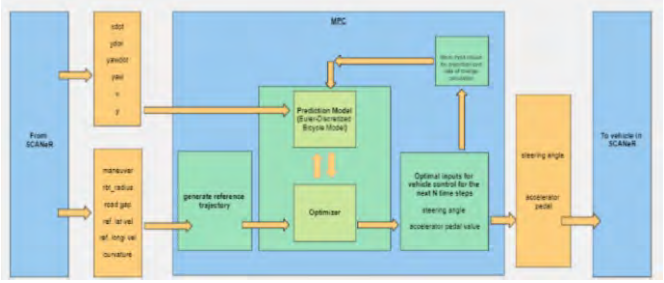


Fig. 2. MPC-architecture

controller is used to minimize the error between the reference and measured lateral velocities. A gain table is used to convert the output of the PID controller to the desired steering angle value, which is then sent to the vehicle (in the virtual environment) for execution. The tuning of the gain table depends on the steering response of the vehicle and is different for different vehicles. Further, more tuning for the Kp, Ki, Kd parameters is needed for the PID controller, which also varies from vehicle to vehicle and in fact also from maneuver to maneuver.

MPC architecture - Fig. 2 parallely shows the MPC-based control architecture. The data obtained from SCANeR remains the same, except for road gap which is not needed for an Fig. 2. MPC-architecture MPC implementation. As seen from Fig. 2, most of the data needed is continuous and constant with regards to maneuvers, or terrain or vehicle. Vehicle data needed - longitudinal and lateral accelerations, velocity, position (global). Road data Curvature, heading, elevation (if needed). Maneuver data Maneuver type (drifting, roundabouts, turning etc.), reference values of the vehicle data that we wish to track (reference velocities and acceleration). Based on the maneuver data, and the necessary NCAP protocols for the maneuver, a trajectory generator block generates the reference set of waypoints to be followed. (Note: The location of the waypoints differs based on the reference velocity and acceleration). The vehicle data (longitudinal and lateral velocity and acceleration and vehicle position) is used by the Prediction block of the MPC controller to the predict the state of the vehicle given different inputs. The state of the vehicle at any instant in time is given by the vector - $[x\ y\ \omega\ x\ y\ \omega\ ]'$. The MPC controller works to ensure the vehicle state is close to the reference state over the duration of the maneuver. The control input to the vehicle is a 2x1 vector given by - [δ ax]' which denote the steering angle (between -540 to 540 degrees) and throttle pedal ratio value (0-1) respectively. The prediction block basically uses an Euler-discretized version of the Bicycle model to predict the output state based on any given set of input values. It iterates over several input values, and an optimizer framework parallely calculates the input vector which will minimize the error between the vehicle state and the reference state over the next 'N' time steps where N is known as the prediction horizon. The reference states for these time steps are obtained using - the 'N' next nearest set of points from the discretized path are chosen to be followed. Since the N points that are immediately ahead of the vehicle in the path keep changing at every time-step, the accuracy of the controller improves as we allow for the change in curvatures to be accounted for. The output of the MPC controller would be an Nx2 matrix denoting the required input values for the vehicle at each of the N time steps in the future in order to minimize the error between the reference and executed path. Finally, the first of these N sets of input vectors is sent to the vehicle, and the entire process is repeated at the next time step based on the new state of the vehicle. The optimization framework used is given by CasADi [3] which has several inbuilt solvers including IPOPT, QPOases, SQPmethod etc.

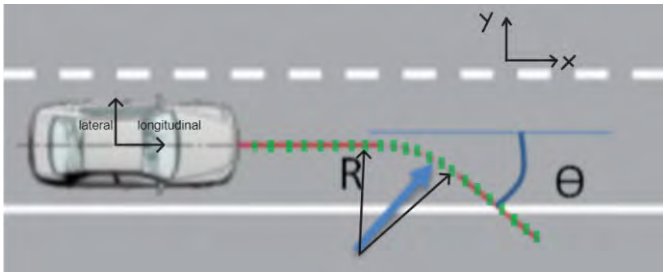


Fig. 3. Green waypoints to be followed

This architecture ensures flexibility with respect to maneuvers in the sense that the architecture for different maneuvers would only differ in the trajectory generation block. Standardization is possible in case of trajectory generation since a protocol has been set by NCAP, which defines the path a vehicle should take for a given maneuver. Moreover, the optimization and prediction blocks are independent in functionality with respect to the trajectory generator block. We shall discuss a short example below on the MPC control in drifting maneuver for LSS (Lane support system).

MPC Example (LSS) - We consider a standard NCAP regulatory scenario with the vehicle moving

on a 3-lane road with a constant speed (longitudinal) of 72km/hr. According to the NCAP requirements, the vehicle should start drifting once the speed of 72 kmph has been stable for 5 seconds. It undergoes a lateral drift in the positive y direction, while following a straight line - arc - straight line path. The lateral velocity to be achieved for the drift is specified to 0.5m/s (which determines the slope of the latter straight line) and the allowed radius of the turning portion is set to R = 1200m. The values of the radius of curvature and lateral velocity are set by NCAP and our vehicle must follow the path generated in Fig. 3 in order to pass the regulatory standards, first in simulation and then on-road. The regulatory poses several such combinations of lateral velocities (between 0 to 2m/s) and turning radii(400m to 1200m) and we aim to have a controller which will successfully guide the vehicle along all possible drifting paths.

Path generation - We discretize the straight line - arc straight line path with points at regular distances on the straight lines, and points at regular angular separation on the arc. The 'density of points' i.e points-per-meter of the path length will determine the distance between consecutive points and thus the performance of the controller as well. Fig. 3 shows the waypoints overlaid on the reference path in green. The set of points is stored in a NUMx2 matrix where NUM is the total number of points from the beginning to the end of the path. The first column is the x-coordinate of points and the second column is the y-coordinate of points in the order in which we want them to be followed by our vehicle. For a constant distance of d between 2 consecutive points (along the path), the x co-ordinates of the points on the first straight line will be at regular intervals of d and the y co-ordinates will all be 0. For the arc, the start and end angles of the arc are 0^c and

$$\theta = \tan^{-1}\left(\frac{v_{lateral}}{v_{longitudinal}}\right)^c$$

and thus, the arc-length would be $l = R\theta$. The angular separation between 2 consecutive points would be $(d/R)^c$ and thus the number of points on the arc would be $\theta/((d/R))^c$. For the latter straight line, the slope would be given by

$$m = \frac{v_{lateral}}{v_{longitudinal}}$$

and thus, the x-spacing between 2 consecutive points would be $d\cos(\tan^{-1}(m))$ while the y-spacing would be given by $d\sin(\tan^{-1}(m))$. The number of points on the 2 straight lines would depend on when one would like to start and end the drifting maneuver, which will determine the length of the 2 straight lines and eventually the number of points on them. Once we have this matrix of points, we send it to the prediction-optimization loop. The prediction horizon N = 10, the time step chosen is 0.01s and the control horizon Nc = 3. We use a multi-shooting approach as implemented in [6] in order to get the control inputs which minimize the error between the desired states and the states which the vehicle actually attains. From the reference set of points, at every time step, we choose the N nearest points to the current position which are ahead of the vehicle on the reference path, to be followed. This restricts the size of our optimization problem, and also ensures are quicker response at sharper turns. Several MPC implementations use polynomial interpolation to generate this reference path for every time step while this MPC implementation has been inspired from [5] which uses are similar multi-shooting approach for CarSIM simulations. The prediction model predicts the future positions using the Euler-discretized bicycle model and then calculates the error between the reference and predicted states. Based on these predictions, the optimizer comes up with an improved set of inputs which will further reduce the error calculated by the prediction model and the loop goes on until we have an optimum value. The optimizer uses the IPOPT solver We have an Ncx2 matrix as the output of this prediction-optimization loop which gives the steering angle and throttle pedal value to be given to the vehicle for the next Nc time steps. The first out of these Nc sets of control inputs is given to the vehicle and the process is repeated on the next time step.

The parameters N and Nc directly influence the performance of the controller but they're kept constant throughout the simulation and across maneuvers and vehicles. The density of points

chosen on the reference path is the one crucial parameter that influences the performance and an empirical linear relation was obtained between the density of points and the velocity and length of the path that needs to be traversed.

$$NUM_{total} \quad \alpha \quad \frac{L_{path}}{v_{longi}}$$

III. RESULTS

We now integrate the MPC-controller with the PID-based control model in Simulink. For the purpose of this project, we restrict to lateral control

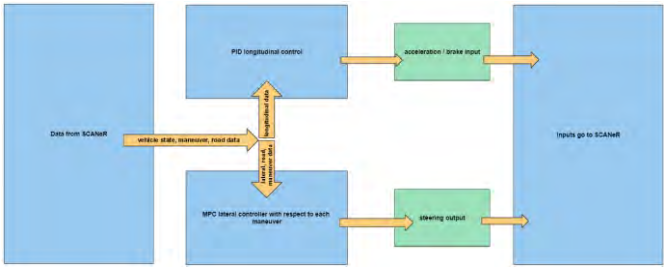


Fig. 4. Final high-level control architecture

with MPC and maintain a PIDcontroller for longitudinal(velocity and acceleration) control. The reason for choosing such a framework is because the actual vehicle dynamical model is a black-box. Thus the actual correlation between the throttle pedal value and the vehicle's attained acceleration is not known. A simple welltuned PID controller helps resolve this, while also reducing the computational cost for the MPC controller since it now only controls the lateral motion of the vehicle. Moreover, it was also observed that such an implementation improves the path tracking accuracy and has been adopted in several MPC implementations in literature like [7] and [8]. In order to test this implementation, we have scenarios setup in SCANeR for the following maneuver - lateral drifting (LSS), 90° right and left turns at intersections, roundabout navigation - at all possible exits. All these scenarios have terrains and vehicle speeds as suggested in the Euro-NCAP protocols for testing. In these scenarios, the controller should be able to make the vehicle track a trajectory compliant with the NCAP protocols in order to pass safety regulatory tests. In the beginning of each of the scenarios, the vehicle starts at rest in the road-lane of interest, and a PID controller helps in attaining the speeds and orientations before the execution of the maneuver starts. Once we are in the maneuver-performing region, (eg. at some distance from an intersection or roundabout, at some specific time interval before we drift etc.) the MPC controller takes over the lateral control and makes the vehicle follow the desired path in order to perform a specific maneuver. Most maneuvers included in the NCAP protocol require the vehicle to have a constant speed between certain range (depending on the maneuver) and a PID controller works best to maintain this constant speed at a low computational cost. This switch from PID to MPC for lateral control has a low latency and the distribution of vehicle control between 2 controllers effectively ensures optimal vehicle performance and low latency for realtime simulations as well. A total controller architecture with both the PID and MPC controllers looks as shown in the Fig. 4 above. Note that the trajectory generator block lies within the MPC-block in this architecture, and receives the road-data and maneuver data.

As observed, the data communication blocks remain the same as in Fig. 3 which communicate data from SCANeR to the Simulink model and then send the control commands from Simulink to SCANeR. A simple switch helps us switch between MPC and PID for lateral control. Within the MPC controller block, an additional switch case is added which helps determine which out of the 4 maneuvers mentioned above are to be executed. For each of the maneuvers, only the reference trajectory generation differs since it is based on the absolute road geometry and scenario, while the controller working remains the same.

A. Lateral Drifting for Lane Support System(LSS)

This maneuver essentially involves the drifting of a vehicle over a large radius and a small angle (≈ 1°) away from the ideal straight-line lane-center trajectory. The objective of the maneuver is to attain a constant lateral velocity while moving along the green curve and staying between the

5cm tolerance about the reference path shown in black in Fig. 8 below. The first maneuver developed is the one specified by NCAP for LSS test. In this maneuver, as illustrated in Fig, the vehicle is required to follow first a straight path and then a circular path of radius R till a lateral velocity, as mentioned by NCAP, is reached. Once this lateral velocity is reached, the vehicle needs to maintain the heading. The reference path is thus an arc-straight line combination which is discretized using points at specific intervals along the path length. The density of these points (points/m), as discussed earlier, affects the performance of the controller. For a dynamic model, this is a nonlinear behavior and requires a lot of iterations to arrive at optimized values. This is where MPC increases the implementation efficiency of the system. As seen in Fig. 6, the PID-based control model settles for a steady-state lateral velocity offset of about 0.01m/s. This essentially means that the slope of the straight-line portion of motion

$$\left(\frac{v_{lat}}{v_{longi}}\right)$$

is slightly different as compared to the desired slope. Thus the PID-control path is not exactly the same as the desired path, which is not the case with respect to MPC as seen in Fig. 5. Although the MPC controller results in a higher overshoot while attaining the desired lateral velocity, the observed overshoot is within the allowed tolerances. Moreover, this overshoot settles off quickly without giving any steady state lateral velocity error. Hence, as observed, the vehicle follows the path suggested by NCAP within the 5cm tolerance band. Table 1. in Fig. 7 shows the comparison between MPC and PID controllers for this maneuver.

B. Roundabouts

To test the scalability of the MPC architecture, it is tested against a roundabout defined by a radius R and number of exits. In this maneuver, we wish to guide our vehicle about a roundabout of known radius given the exit to be taken. Using the work done in [(Bertolazzi; Frego, 2014)], the controller first determines the path based upon the roundabout radius, entry point and the exit. We use a clothoid-arc-clothoid combination, where a clothoid curve is used for entry and exit of the roundabout circle and a circular arc through the lane center of the desired lane is used to move along the circular portion of the roundabout.

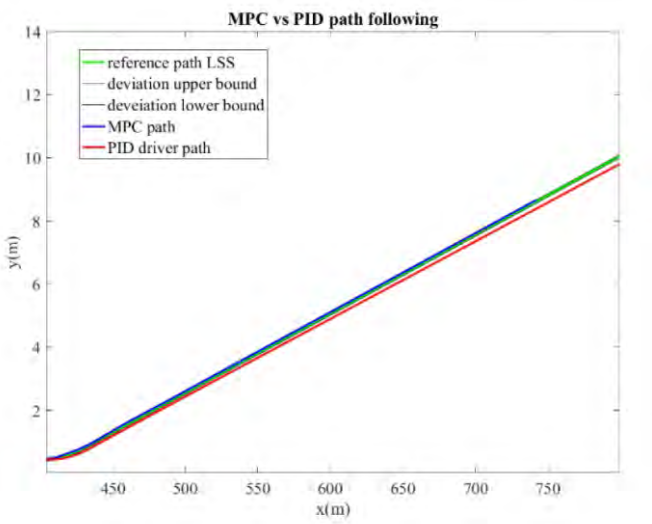


Fig. 5. LSS PID vs MPC path following

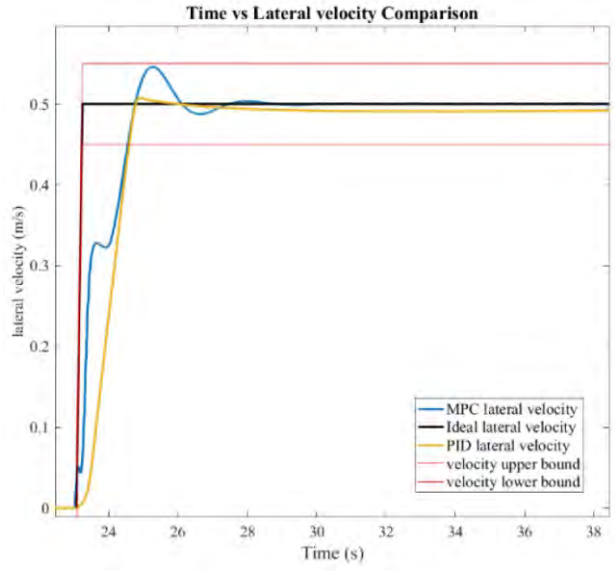


Fig. 6. MPC vs LSS lateral velocity

Table 1 PID vs MPC performance

Parameters	PID	MPC
Steady State Lateral velocity error (m/s)	0.01	0
Steady State path offset (m)	0.1	0.05
Number of iterations	30	1

Fig. 7. MPC vs LSS performance comparison

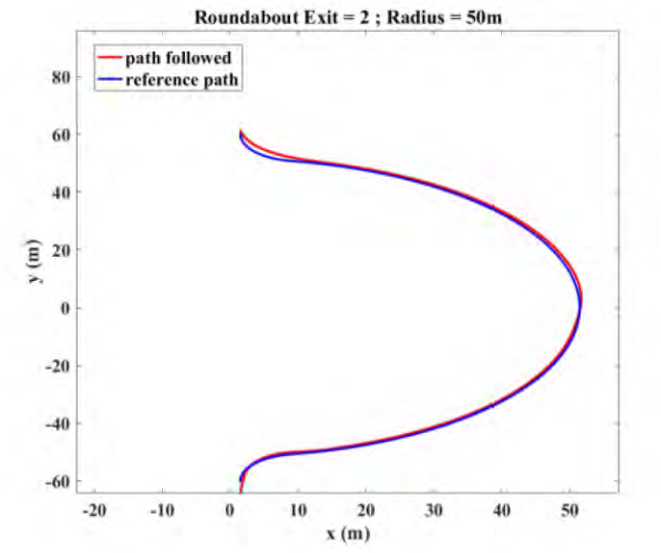


Fig. 8. Roundabout Exit-2

The start radius of the entry clothoid is very large, and the start angle is 10°. Since we have 2 symmetric clothoids for entry and exit, the arc actually extends for D −20° where D denotes the difference between the initial and final heading of the vehicle after completing the maneuver. Thus for if we take the first exit : D = 90°, if we take the second exit D = 180° and so on. The end-radius of this clothoid is given by $R = r_{roundabout} + r_{lane-offset}$. The clothoids are generated by the [1] calculations. As seen in Fig. 9, the proposed controller can create the path and the guide the vehicle along it with minimum deviation. Usage of open loop PID approach will require a new strategy for computing the path and will require lot of iterations on steering angle and PID gains. Additionally, this will be a function of the dynamic behavior of the vehicle. In case of MPC, we observe that it performs for vehicles with different dynamics without any additional tuning. Again, as desired by NCAP, the MPC controller maintains less than 5cm deviation from the reference path proposed using the above scheme. Fig. 8 shows the path take for navigating through exit 2 of the roundabout.

The PID-based longitudinal control helps maintain a constant speed of 20km/hr while the MPC controller controls the steering of the vehicle. This strategy works successfully with similar accuracy in path-tracking for all speeds between 1030 km/hr which are suggested by NCAP for moving through roundabouts. Note that this scheme of implementations is generic in the sense that the exits of the roundabout need not be at 90o apart each. They can be any angle apart, specifying which, our trajectory generator will automatically generate the appropriate clothoid-arc-clothoid combination. [1] essentially helps us fit a clothoid between 2 points, knowing the start and end angle of the clothoid, and according to [4] it is also a unique curve that would fulfil these requirements.

C. Right Turn

In this maneuver we wish to make the vehicle take a 90° right turn at an intersection while following the reference path given by (Euro NCAP). This path is a combination of entry clothoid followed by an arc and an exit clothoid. Using equations of clothoid and arc, the proposed architecture computes the path and the required steering angle to follow the computed path. Again, we compare the MPC performance with the PID performance as shown in Fig. 12. The mean deviation from the path is lesser in MPC while also maintaining the heading parallel to the referenced path throughout the maneuver. The mean deviation is calculated as the mean distance from the 4 main points shown in Fig. 9 as the vehicle tracks the reference path. This performance can be improved by optimizing the number of reference points with respect to the curvature and velocity. Maintaining a parallel heading for this maneuver is critical for correctly simulating other (Euro NCAP) safety regulatory cases like pedestrian collision. Note: A right-hand turn and left-hand turn are symmetric with only different radii of the arc portions of the turn. The radius and clothoid angles to be used for a given speed is specified by NCAP and accordingly adopted while generating the clothoid-arcclothoid combination using the set of equations below. Fig. 9, 10, 11 show the generation of this clothoid-arc-clothoid path. While performing the calculations, we consider we're aware of X_1 and Y_4 since they are essentially the lane offsets to be maintained in the initial and final lanes we are turning into. The origin is considered to the center of the intersection where the 2 road axes meet. Fig. 12 shows the comparison of the

results of MPC and PID controllers for turning.

α = clothoid angle (rad)
β = arc angle (rad)
$2\alpha + \beta = \pi$
L = length of clothoid
R = radius of arc (m)

$$L = 2R\alpha$$
$$A^2 = RL$$
$$Y_{clo1}^{dist} = L + \frac{L^5}{40A^4} + \frac{L^9}{3456A^8}$$
$$Y_{circle}^{dist} = Rsin(\beta)cos(\alpha) - R(1 - cos(\beta))sin(\alpha)$$
$$Y_{clo2}^{dist} = \frac{L^3}{6A^2} - \frac{L^7}{336A^6} + \frac{L^{11}}{42240A^{10}}$$
$$X_{clo1}^{dist} = \frac{L^3}{6A^2} - \frac{L^7}{336A^6} + \frac{L^{11}}{42240A^{10}}$$
$$X_{circle}^{dist} = Rsin(\beta)sin(\alpha) - R(1 - cos(\beta))cos(\alpha)$$
$$Y_{clo2}^{dist} = L + \frac{L^5}{40A^4} + \frac{L^9}{3456A^8}$$

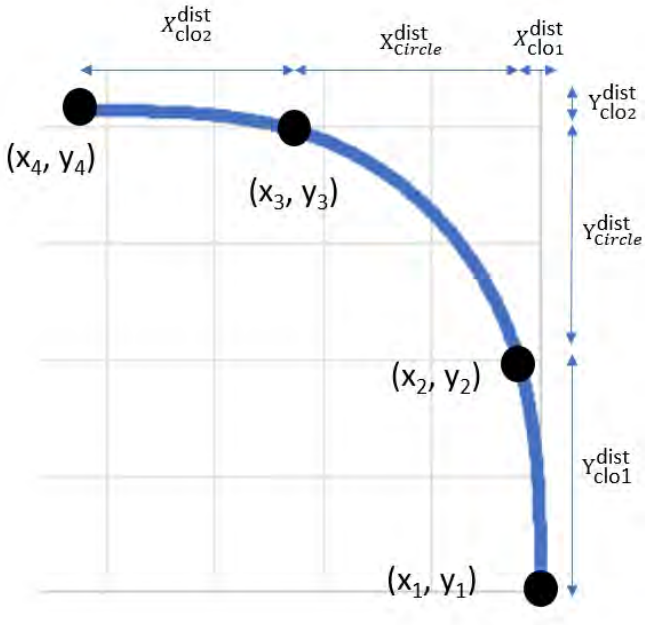


Fig. 9. Generating reference path

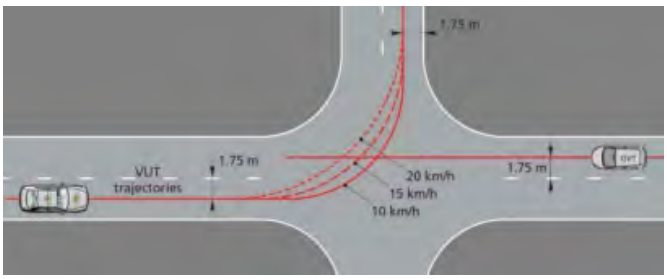
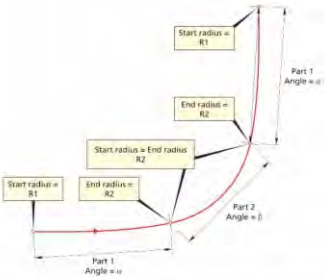


Fig. 10. Reference path for turning



Test speed	Part 1 (clothoid)			Part 2 (constant radius)			Part 3 (clothoid)		
	Start Radius R1 [m]	End Radius R2 [m]	Angle α [deg]	Start Radius R2 [m]	End Radius R2 [m]	Angle β [deg]	Start Radius R2 [m]	End Radius R1 [m]	Angle α [deg]
10 km/h	1500	9.00	20.62	9.00	9.00	48.76	9.00	1500	20.62
15 km/h	1500	11.75	20.93	11.75	11.75	48.14	11.75	1500	20.93
20 km/h	1500	14.75	21.79	14.75	14.75	46.42	14.75	1500	21.79

Fig. 11. Turning - calculations

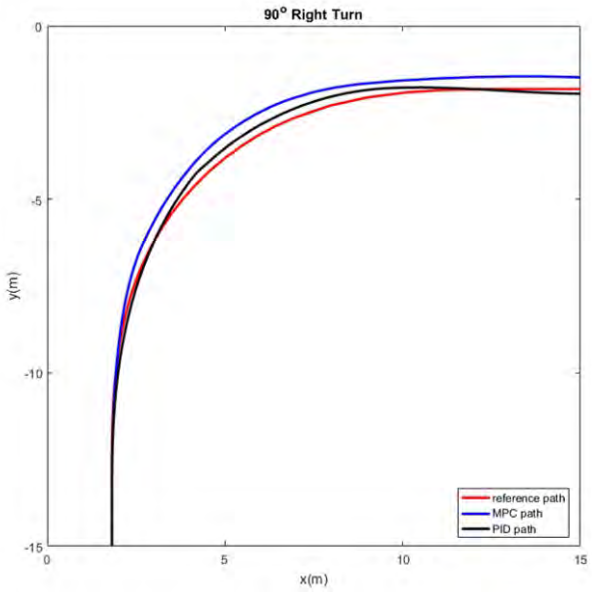


Fig. 12. Right Turn results

IV. CONCLUSION

This study has developed an MPC-based trajectory planning and tracking control strategy to help the ego vehicle perform maneuver in a discrete virtual environment. The results showed that the MPC-based trajectory planning and tracking control

improves tracking accuracy, reduces the need of tuning and can be adapted to changing road topologies with minimum changes. The proposed approach provides a novel and practical solution to increase the scope of scenario-based testing to complex road environments. The proposed architecture comprising of PID and MPC controllers for longitudinal and lateral control respectively has a very low latency in realtime execution and within the same framework, one can also add additional maneuvers for execution solely by editing the reference trajectory generation scheme for the given maneuver. This generation can be generic in the sense that it can take into account various terrain and road parameters like road radius, straight-line heading etc. and thus make the controller more flexible for the entire family of similar maneuvers.

ACKNOWLEDGMENT

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Vibration Analysis of Aircraft Pipelines to Generate Inputs for Clearance Checks in DMU

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Abstract - Aircraft systems comprise of various structural fittings which are subjected to continuous vibrations during flight. Pipebutting is often an issue in operational aircraft and it is essential to ensure sufficient clearance between pipelines and adjacent structural members or wiring looms. The major sources of excitation in an aircraft are air flow-induced vibrations, pressure fluctuations, engine vibration, noise, and vibration transmitted through the landing gear. This paper aims to compute dynamic response of aircraft pipe lines subjected to these excitations. Commercial FE Software MSc/Nastran has been used to carry out dynamic response analysis of pipelines to random, harmonic and transient excitation. The output displacements are provided to the DMU team in ADAMS format. Typical results for a sample pipeline are presented. The novelty of this work lies in the methodology which has been established for generating vibratory responses of pipelines and providing them in a convenient format which enables quick checking of clearances of pipelines in DMU. These studies will also help in giving inputs to the layout team on locations and numbers of intermediate supports to be provided to ensure that displacement response of pipelines under vibratory loads are well within the allowable clearances.

Keywords -
Aircraft pipelines, Structural Dynamics, Random response, Transient response

I. INTRODUCTION

Aircraft systems comprise of various structural fittings which are subjected to continuous vibrations due to aerodynamic, engine or ground load excitation. Generally, pipelines in aircraft are configured in bent lines and tend to cross over each other or lie close to structural members or wiring looms due to the space constraint. The gaps between these pipes and the adjacent accessories are normally very small. Hence, it is essential to ensure that butting does not occur between them during flight operations. Clearance checks are usually made in the Digital Mock-up Unit (DMU) prior to lay-out in the actual aircraft.

Random and transient response analyses are carried out for these pipelines to estimate their dynamic displacement responses. The results will be provided to the DMU Team for clearance checks. These studies will be useful to check whether vibratory responses are causing a reduction in the gap between members resulting in butting with the adjacent members.

The next section describes FEA modeling and solvers used in the present study. Results are discussed in the following section. The paper ends with conclusions from present study, where future works are also discussed.

II. ANALYSIS

A. FEM Description

A dynamic analysis is carried out in MSC Nastran [1]. The pipes are modelled using 1D beam elements (Bar2 in Nastran). The CAD and FE Models of a typical pipeline are shown in Figure 1. To simulate the fuel distribution, point masses (CONM) are lumped at nodes along the length of the pipe. The translations and rotations at the ends of the pipe are constrained appropriately to represent the installed condition in the aircraft.

B. Normal Modes Analysis

As pre-requisite, normal modes analysis is carried out on each pipe with the boundary conditions as mentioned above. The mode shapes and natural frequencies up to 2000Hz are extracted. This covers the frequency range of excitation likely to occur in the aircraft operating environment. It may be noted that the pipes whose natural frequencies fall within 100 Hz are likely to respond to structural vibration. Excitation coming from the engine operation is likely to excite those with natural frequencies in the range 100-300 Hz.

C. Response Computations

Dynamic response analysis is carried out on the pipes using enforced acceleration method of MSc Nastran. Random, Transient and/or Harmonic response analyses are carried out depending on the type of input excitation. Random response analysis is carried out with input excitation as per MIL-810F [2]. According to this specification, the connection points of the pipe are to be subjected to random acceleration input along the three principal axes independently to assess the response of the structure. Transient analysis is carried out on the pipes where time domain vibration data are available from accelerometers mounted inside the airframe.

The displacement responses at the required nodes are extracted. Since the displacement responses are to be provided to the DMU team, they are considered with respect to the aircraft co-ordinate system. The maximum displacements obtained and the corresponding 3 values are provided to the DMU team to check the tolerances between the pipes and surrounding structures. The results are provided in MSC ADAMS format, which is compatible with CATIA. These values are provided to ensure a complete vibration volume envelope surrounding the pipe.

III. RESULTS AND DISCUSSIONS

The results for the sample pipeline shown in Figure 1 are given here. Figure 2 shows typical vibration mode shapes for the pipe considered. First and fourth vibration mode is overall bending of the pipe in lateral direction. Second and third vibration mode is overall bending of pipe in the longitudinal direction.

Figure 1(a): CAD Model of a Typical Pipeline installation in aircraft

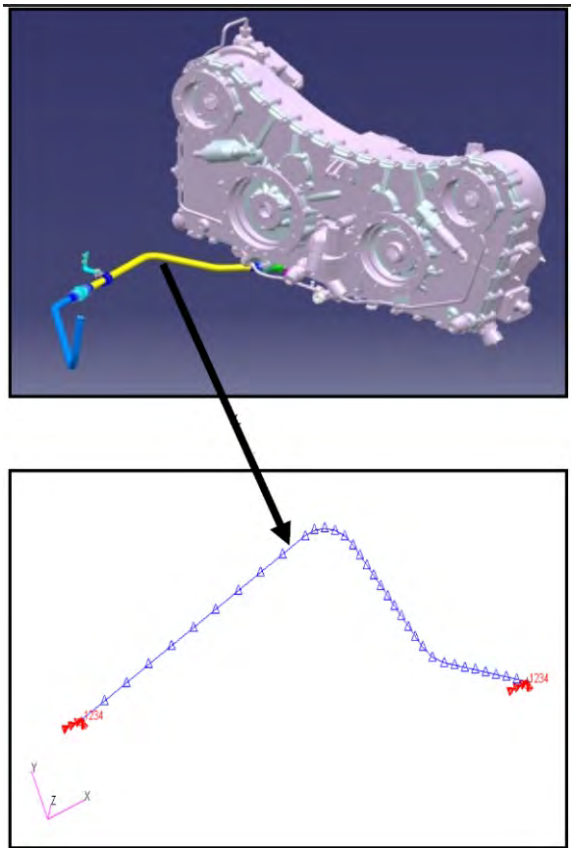


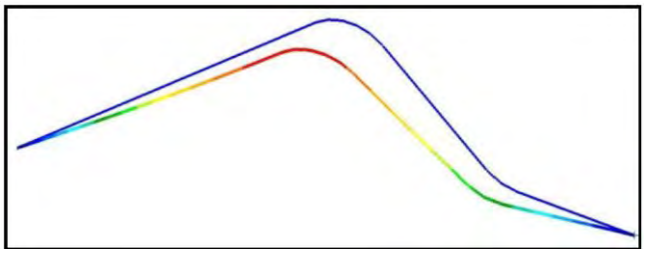
Figure 1(b): FE model Pipe-1

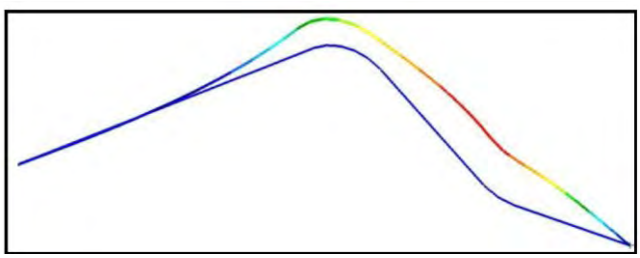
TABLE 1. NORM. MAX POSITIVE DISP. RESPONSE IN ADAMS FORMAT FOR PIPE

T1 (mm)	T2 (mm)	T3 (mm)	R1 (radians)	R2 (radians)	R3 (radians)
0.0014	1.0	0.0054	0.0025	0.0001	0.0028

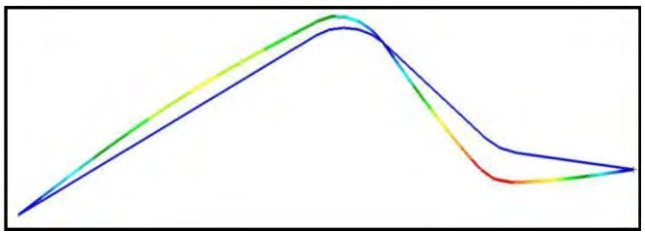
From the random and transient analysis, the maximum displacement responses are plotted in Figure 3. Values have been normalised for sake of confidentiality. And also, the corresponding acceleration response is plotted in Fig. 4. Since the pipeline considered was located in the engine region close to the Aircraft Mounted Accessories Gear Box (AMAGB), transient response computations were carried out with data from accelerometer mounted on AMAGB as input. Typical input excitation in time and frequency domain are shown in Figures 5 and 6. The response in Y- direction is comparatively higher than in the other two directions which accounts for the quasi-static loading coming from the fuselage. Figures 7 and 8 show the displacement response in time and frequency domain respectively for the middle bend location of the pipe during Take-off, landing and maneuver of aircraft. During Take-off, displacement responses of pipe are maximum in all directions as the aircraft engine operates at higher rpm.

The total displacement is a combination of displacements computed from random and transient response analyses. The results indicate that the pipe show greater displacement response close to location of bends. The transverse bending modes are the major contributors to the total displacement response. The typical displacement responses in the format required for DMU checks are given in Table 1.

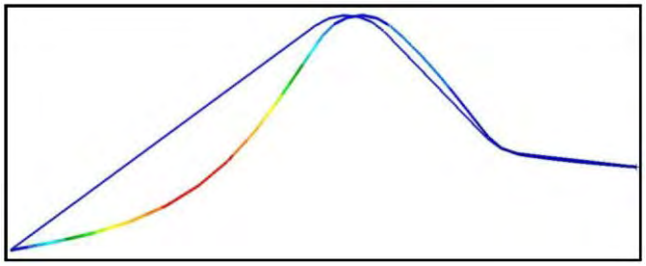




2(b) Longitudinal bending



2(c) Longitudinal bending



2(d) Lateral bending

Figure 2: Modes Shapes

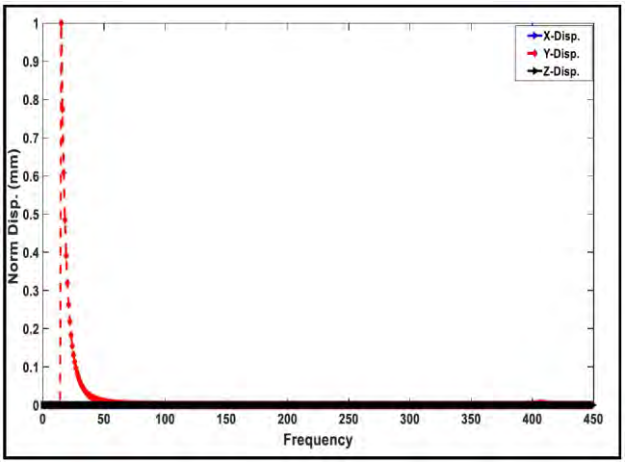


Figure 3: Displacement response of Pipe for Random Excitation Input.

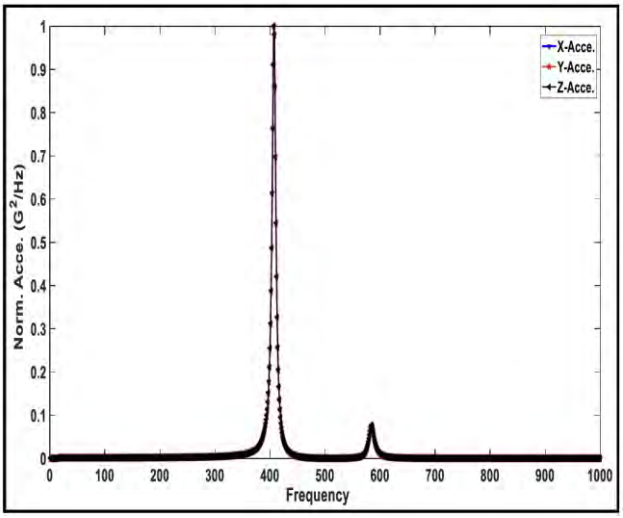


Figure 4: Acceleration PSDF response for Random Excitation Input.

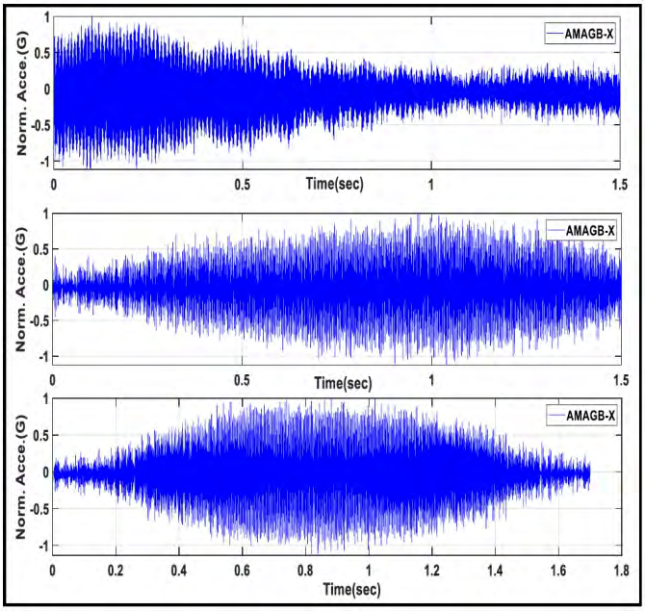


Figure 5: Acceleration Time Response for AMAGB during different aircraft manoeuvre (Landing, Manoeuvre and Take off)

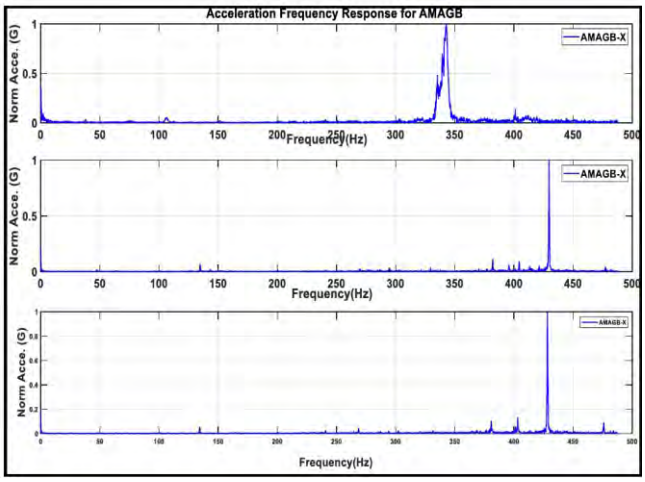


Figure 6: Acceleration Frequency Response for AMAGB during different aircraft manoeuvre (Landing, Manoeuvre and Take off)

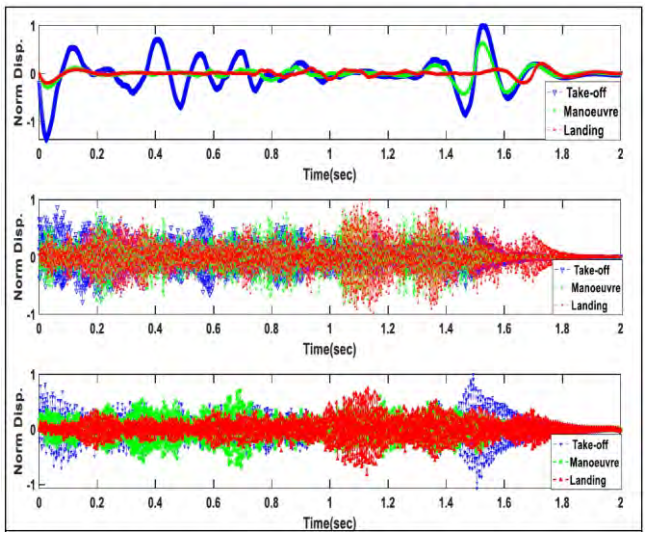


Figure 7: Displacement Time Response at Mid-Section of pipe

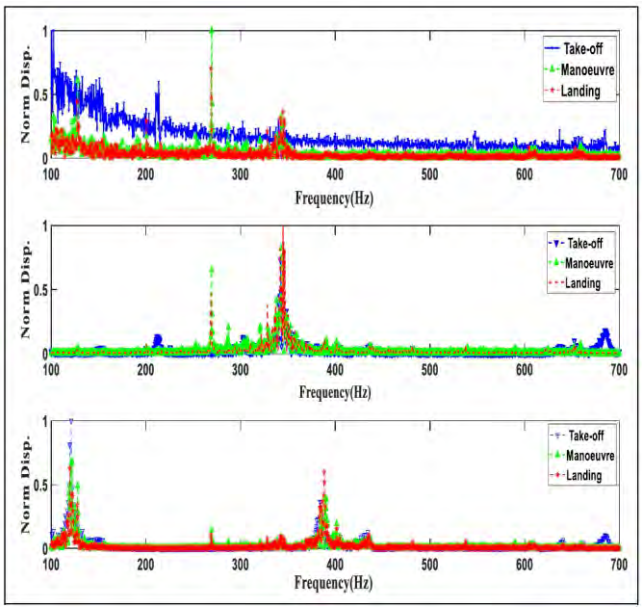


Figure 7: Displacement Time Response at Mid-Section of pipe

Both positive and negative values are provided to DMU Team so as to ensure a complete vibration volume envelope surrounding the pipe.

IV. CONCLUSION

Dynamic response of aircraft pipelines subject to random and transient excitation are computed with the objective of providing inputs to DMU for clearance checks. Commercial FE analysis software MSc/ Nastran was used for simulation. Displacement responses are extracted from random and transient response computations. These are provided in ADAMS format to DMU for clearance checks using the vibration volume utility. A methodology has been thus established for generating and providing vibratory response in a convenient format for clearance checks of pipelines in DMU. This can be applied in future for carrying out pipe butting checks. Such studies will also aid in identifying the areas which need

attention during pipeline layout routing for intermediate supports to ensure that displacement response of pipelines under vibratory loads are well within the allowable clearances.

ACKNOWLEDGMENT

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Effective Model-Based Systems Engineering Framework for Logic Intensive Applications: Digital Anti-skid Brake Management System Case Study

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Abstract - The Digital Anti-skid Brake Management System (DABMS) for an aircraft represents an advanced technological solution aimed at augmenting the performance, safety, and efficiency of aircraft braking systems. The modern Digital Anti-skid Brake Management System employs fully digital and integrated brake-by-wire system, comprising of multi sensor integration, advanced robust and adaptive wheel slip control laws, fault tolerance and redundancy, diagnostics and health monitoring, and human machine interface, thus making it multi-disciplinary. This necessitates rigorous testing and validation to meet the aviation regulatory standards. The design process of the Digital Anti-skid Brake Management System necessitates constant adjustments to meet evolving technical and user requirements. This highlights the significance of modern Model-Based Design (MBD) techniques to efficiently accommodate changes and expedite product development.

In this paper, we present the utilization of Model-Based Systems Engineering (MBSE) to implement a Digital Brake Management System for a light transport aircraft. The case study demonstrates the efficacy of the Model-Based approach, particularly in the context of Model-Based Testing. The quantitative result shows advantage of the Model-Based approach for enhancing the system design development and testing, offering effective change control and streamlined implementation processes.

Keywords - Model-Based Systems Engineering (MBSE), Hardware-in-the-Loop (HIL), Software-in-the-Loop (SIL), Model-Based Testing, Safety Critical Systems, Digital Anti-skid Brake Management System, PMTE

I. INTRODUCTION

Model-Based Systems Engineering (MBSE), Hardware-in-the-Loop (HIL), Software-in-the-Loop (SIL), and Model-Based Testing are concepts industry has adopted for accelerating the development process without compromising on function-

ality, performance, and safety[1]. The Model Based System Engineering provides a synergy amongst the stakeholders to ensure delivery of the right system within the stipulated time.

Controls algorithms aid in leveraging designs to provide stability and improve transient performance and operability for complex closed loop systems such as AFADEC, digital fly-by-wire system, digital brake management system to name a few.

This paper discusses the usage of Model Based System Engineering for implementing Digital Anti-skid Brake Management System (DABMS) for a light transport aircraft. This is first of its kind development in the country where the challenge was to develop aircraft specific Digital Brake Management System using Model Based System Engineering technique. The effort to take up Model Based System Engineering approach was to use advantage of semantic translation of requirements into a design model. Additionally, application of MBSE techniques helped to achieve rapid simulation and testing in Model-in-loop (MIL), Software-in-the-Loop (SIL) and Hardware-in-the-Loop (HIL) environments, thereby ensuring accurate and efficient implementation with respect to the functionality and performance.

II. DIIGITAL ANTI-SKID BRAKE MANAGEMENT SYSTEM

The Digital Anti-skid Brake Management System is designed to be a Fail-Op, Fail-safe system in which a single failure provides degraded functionality. The next failure transits the system to a safe state with annunciation to the pilot. The Digital Anti-skid Brake Management System architecture comprises components such as pedal sensors, hydraulic supply, wheel speed sensors, pressure sensors and electro hydraulic servo valves. The system interfaces with other subsystems of aircraft as listed below;

- Brakes and Wheels
- Servo Valves (Brake Pressure modulation)
- Landing Gear (Weight on wheel)
- Avionics (DGPS, Displays, Brake Controller)

The Digital Anti-skid Brake Management System architecture is shown in Figures 1. Digital Anti-skid Brake Management System has two functional modes viz, Proportional Braking and Anti-skid braking. In the proportional braking pilot brake demands are translated to brake torque on wheels, while Anti-skid function modulates the brake pressure to the wheels based on Pilot's demand and a feedback signal derived from free wheel speed and braked wheel speed.

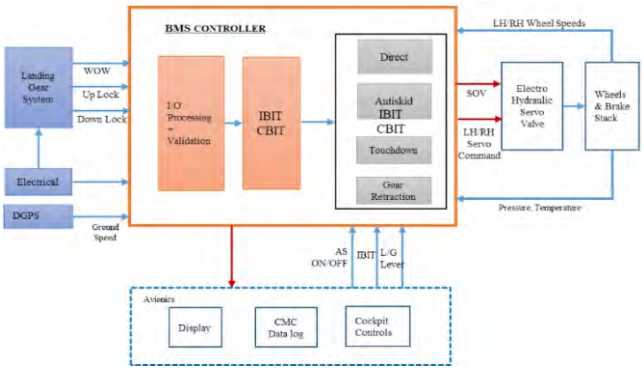

Figure 1: Digital Anti-skid Brake Management System Architecture

This system is safety critical, hence appropriate annunciation of caution/warnings and fault isolation in the event of failures has been devised. The failures are detected based on monitors that sense failure/malfunction of Pedal transducers, wheel speed sensors, servos, and brake pressure transducers. Upon detection of anti-skid fail caution, the brakes are still available and an anti-skid fail warning is annunciated to the crew who has to switch to proportional mode using the anti-skid switch. However, upon detection of brake failure, the brake fail warning as well as anti-skid fail caution are annunciated to the crew who is then required to use the emergency brakes. In order to make it fail safe, in the event of any of the failures, the servo commands are set to zero

The brake management system architecture shall meet the following functional requirements.

- Braking shall be provided on left and right main wheels
- Both wheels shall be braked independently
- System has Power On Built in Test, Continuous Built In Test, Pre-flight Test, and Failure

detection and annunciation. A brake command must always be provided during Rejected Take-Off (RTO).

- Antiskid shall hold the fixed reference slip based algorithm
- Antiskid protection shall be active above the cut-in aircraft ground speed
- Antiskid protection shall be deactivated below the cut-out aircraft ground speed

III. FRAMEWORK FOR IMPLEMENTATION OF DIGITAL ANTISKID BRAKE MANAGEMENT SYSTEM

The proposed framework has been developed for logic intensive closed loop systems, BMS being one of such systems. Figure 2. shows the model-based systems engineering framework adopted in CSIR-NAL. The organization is currently utilizing a model-based system engineering framework to develop safety-critical logic-intensive applications like Digital Anti-skid Brake Management System, stall warning and protection system , Automatic Flight Control System and Environment Control System. The framework incorporates model-based safety assessment techniques, requirements, design methodology, and semantic translations of simulation test vectors into hardware software integration test cases.

As shown in the Figure 2, the system safety assessment was appended with a formal method System-Theoretic Process Analysis[2][4] to ensure that all the failure scenarios including the user actions are captured. The integration with CAMEO provided a report generation capturing System-Theoretic Process Analysis outputs with its effects. These inputs are used to refine the control logic models. Functional requirements in the form of specification model are semantically translated to the design model as part of Software Development Life-Cycle. The test vectors with safety scenarios used in validation of the specification model are reused of the design model and the embedded code on the target in real-time. The response of the specification model, design model and the embedded code to the test vectors are compared for acceptance criteria by the systems team for clearing the system for aircraft integration and testing.

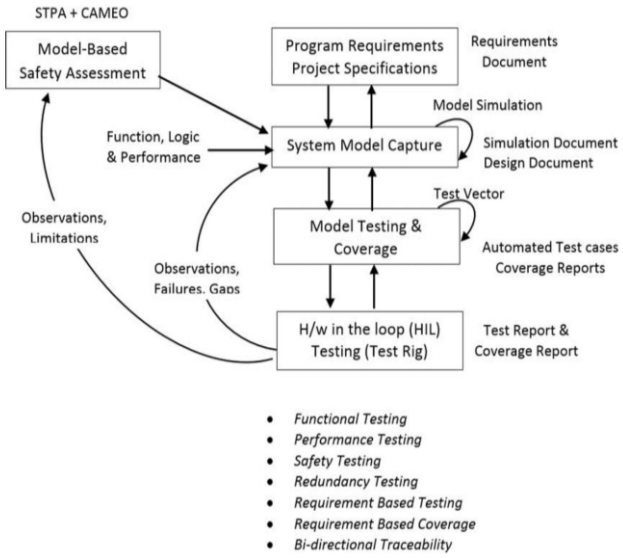

Figure 2: Model based system engineering

Figure 3 shows the pictorial view of the translating the simulation test vectors to the system test cases using the Model-Based approach and comparison of the test results of specification model, design model, and embedded target. The semantic translation of the test vectors from the simulation to test rig, validates the correct translation of the logic to the embedded target and assures the correct implementation.

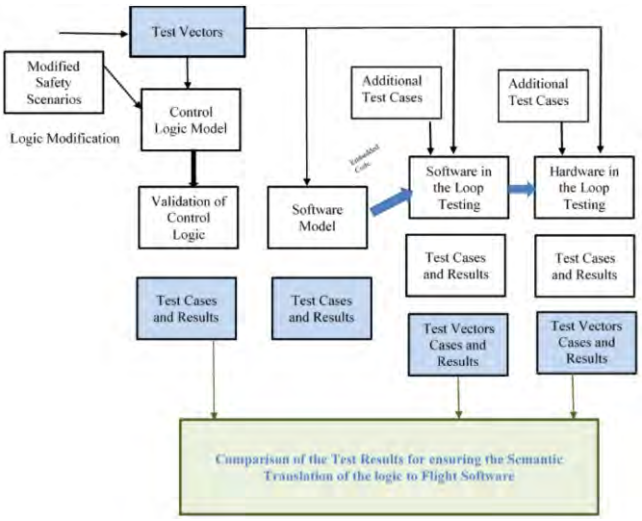

Figure 3: Comparison of model-based approach for Digital Anti-skid Brake Management System

This approach provides an effective way of implementation and validation a logic intensive application, more so when done for the first time without any a-priori reference and benchmarks.

IV. MODEL BASED SYSTEM ENGINEERING METHODOLOGY

Model-Based Systems Engineering (MBSE) methodology is a collection of interconnected procedures, techniques, instruments, and work environments that support the systems engineering discipline in a "model-based" or "model-driven" setting. For the purposes of this paper, methodology is distinguished from process, methods, and tools using the following definitions from [6].

A process (P) is a logical arrangement of actions taken to accomplish a specific goal. A process outlines "WHAT" needs to be done without describing "HOW" to complete each activity.

Each task's "HOW" is defined by a method (M), which is made up of ways for carrying them out.

When used with a specific method, a tool (T) is an instrument that, if used correctly and by the right person, can increase the task's efficiency.

Environments (E) are the surroundings, external items, conditions, or factors that affect how an object, a person, or a group of people acts. The tools and techniques used on this project must be integrated and supported by this.

Using the definition given above, A methodology is a grouping of associated procedures, techniques, and equipment. A methodology, which may be thought of as the application of related procedures, approaches, and tools to a class of issues that all share a characteristic, can be thought of as a kind of "recipe" [6]. By broadening the scope of this description, an Model Based System Engineering methodology can be defined as a group of linked procedures, techniques, and instruments that serve the field of systems engineering in a "model-based" or "model-driven" context as depicted in the Figure 4.

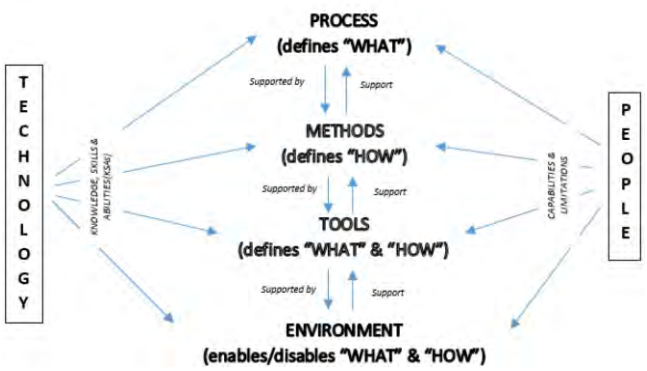

Figure 4: The PMTE elements and effects of technology and people (Copyright © 1996 CRC Press, Inc)

In the Model Based System Engineering framework adopted in CSIR-NAL, the PROCESS is to develop the safety critical application viz., Digital Anti-skid Brake Management System, stall warning and protection system and Automatic Flight Control System. The METHOD used to generate the test case is System-Theoretic Process Analysis. Adoption of Model Based System Engineering has helped to address the PROCESS. And TOOLS used are Matlab Simulink, Ansys SCADE Suite, SCADE Design Verifier and CAMEO. The ENVIRONMENT is how easy it was to transact between these various TOOLS using the METHODS to address the PROCESS by the PEPOLE using the TECHNOLOGY System-Theoretic Process Analysis has been used to generate test vectors for the control logic model. The Table 1 – 3[7-10] shows the test cases for malfunction of the Brake System Control Unit[5], Hydraulic Controller and Servo Controller. These test cases were used to design software and hardware provisions to mitigate the malfunctions generated by System-Theoretic Process Analysis [3].

Not providing causes hazard	Providing causes hazard	Too soon, too late, out of sequence	Stopped too soon, applied too long
Control Action: BSCU: BSCU.1 Brake command			
BSCU.a1	BSCU.b1	BSCU.c1	BSCU.d1
No Command during RTO (to V1), resulting in inability to stop within available runway length	Loss of control and occupant injury occurred due to an excessive command input during the landing roll, leading to rapid deceleration.	Damage to the landing gear, and loss of control ensued due to a command issued before touchdown, leading to a burst tire.	Deceleration was compromised as a result of inhibiting the command during the landing roll before reaching the required taxi speed.
BSCU.a2	BSCU.b2	BSCU.c2	BSCU.d2
Insufficient deceleration and the potential for overshooting occurred due to the absence of command during the landing roll.	Insufficient acceleration ensued from an inappropriate command given during takeoff.	Insufficient deceleration and the potential for loss of control and overshooting occurred due to the application of a command more than 10 seconds after touchdown.	The prolonged application of the command during the landing roll led to a runway stoppage.
BSCU.a3	BSCU.b3	BSCU.c3	BSCU.d3
Failure to issue a command during taxi resulted in excessive speed, an inability to stop, or a lack of control over speed.	Inadequate deceleration during the landing roll occurred because insufficient level of command was applied.	The command was applied before the wheels left the ground, and no request for a rejected takeoff (RTO) had been made.	Loss of control and equipment damage occurred due to the application of the command for tire lock until less than 10 seconds before touchdown during the approach.
BSCU.a4		BSCU.c4	
Potential equipment damage during landing gear retraction or wheel rotation in flight may occur when no command is given after takeoff to lock the wheels.		The command was initiated more than 10 seconds into the rejected takeoff, presuming that Autobrake is responsible for braking after the crew has throttled down.	

Table1: Test cases for malfunction of the Brake System Control Unit

Not providing causes hazard	Providing causes hazard	Too soon, too late, out of sequence	Stopped too soon, applied too long
Control Action Hydraulic Controller: HC.1 Open shut- off valve (i.e. allow Servo driven braking)			
HC.a1	HC.b1	HC.c1	HC.d1
The valve was not opened to enable braking when there was no fault requiring the use of alternate braking.	The valve opens to deactivate the alternate braking mode when a fault necessitating alternate braking is detected.	The valve opens belatedly, after servo-driven braking becomes both possible and necessary.	Valve held open too long preventing alternate braking when servo driven braking is not operating
	HC.b1	HC.c1	HC.d1
	The valve is opened to deactivate alternate braking when the BSCU has been disabled by the crew.	The valve is opened after the expected time response when the crew has initiated the BSCU.	The premature closure of the valve prevented braking when it was both possible and necessary.

Table 2: Table 2: Unsafe Control Actions (BSCU Hydraulic Controller)

Not providing causes hazard	Providing causes hazard	Too soon, too late, out of sequence	Stopped too soon, applied too long
Control Action Servo Controller: SC.1 : Servo valve position command			
SC.a1	SC.b1	SC.c1	SC.d1
The valve did not receive a position command when brake commands were issued.	A position command is given to open the valve when no brake commands are received.	The position command is issued too late after the crew has commanded braking.	The valve closed prematurely as a consequence of stopping the position command too early while braking was still active.
	SC.b2		SC.d2
	The valve is closed upon receipt of brake commands by issuing a position command.		The position command, intended to keep the valve open, was issued too long after the brake command.
	SC.b3		
	The position command given is either too low or too high to achieve the intended braking effect.		

Table 3: Unsafe Control Actions (BSCU Servo Controller)

QUANTIFICATION OF THE APPROACH

The efficacy of the proposed framework is quantified by using the test vectors from the simulation mode to the embedded code using model base engineering. The BMS simulation model are translated to SCADE model. The STPA scenarios are used to make the BMS model robust from the failure scenario perspective. The test vectors consist of functional, performance and safety scenarios which are executed on the SCADE model of BMS. The model test coverage has been achieved by conducting the model testing on the design models. The snapshot of the model coverage report is shown in Figure 5.

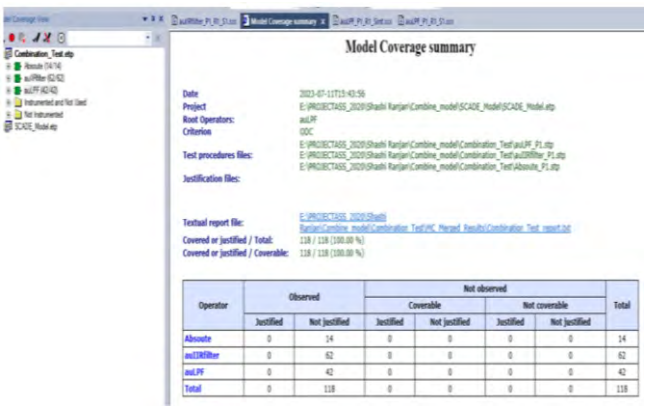

Figure 5: Model Test Coverage using SCADE

In the Figure 5, the table of the detailed count of coverage points must be read as follows:

- In the nominal coverage case, observed coverage points are counted as not justified and represent the overall coverage rate. Any observed point counted as justified should be considered as an error case: a justification is no longer needed
- The count of coverage points that are not observed and not coverable represent dead parts in the analyzed model. The coverage points counted as not justified show that identified parts in the model need justification or design changes.
- The count of coverage points that are not observed and coverable relate to missing test cases. The coverage points counted as not justified show that identified parts in the model need justification or additional tests.

TEST CASES AND EXECUTION

The test cases are translated to be executed on the system level which is generated as an *.CSV file. The test cases in the comma-separated files (.CSV) format are used for executing the model testing in the Real-Time System test.

The test cases generated using this approach can be re-used for executing on the same models in Real-Time System. This reduces the time and effort required to generate and execute the test cases to obtain the test coverage results. The coverage percentage achieved at model and system level provides the confidence of the semantic translation of the model to embedded code.

The inputs will be integrated and fed into the model test execution. The outputs will be captured by the Real-Time System automation framework. The Table 4 shows the comparison of Model Level Testing results with the System Testing results

auLPF/f32Input	auLPF/f32tau	auLPF/boolReset	auLPF/f32Output	System Testing Output	Restult Matrix
0	0	FALSE	0	0	PASS
10	0	FALSE	10	10	PASS
10	20	FALSE	10	10	PASS
10	20	TRUE	0.0012498	0.0012498	PASS
100	20	TRUE	0.012498	0.012498	PASS
100	0	TRUE	100	100	PASS
100	12.5	TRUE	0.019996	0.019996	PASS
100	12.5	TRUE	0.019996	0.019996	PASS
100	12.5	TRUE	0.019996	0.019996	PASS
100	12.5	TRUE	0.019996	0.019996	PASS
100	12.5	FALSE	100	100	PASS
1000	12.5	TRUE	0.19996	0.19996	PASS
1000	12.5	TRUE	0.19996	0.19996	PASS
1000000	12.5	TRUE	199.96	199.96	PASS

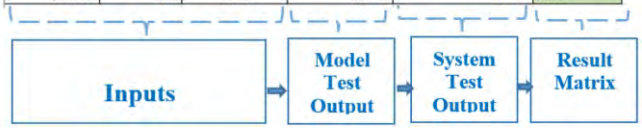

Table 4 Comparison of Model Level Testing results with System testing

CONCLUSION

The model-based engineering framework with STPA proves the efficacy for control intensive applications. Case study of the DASBMS implementation using this approach has shown positive results.

Model Testing, Software-In-Loop testing, Hardware-In-Loop testing results for the simulation test vectors and its coverage is same across the testing levels. This provides the quantification of the framework which uses model-based approach augmented with STPA for a robust design.

With the ground runs and taxi trials of the aircraft, the algorithms can be further fine-tuned in light of availability of actual test data.

ACKNOWLEDGEMENT

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Enhancing Efficiency and Standardization in CAE driven Automotive Product Development through Template based Automation for Load Case Setup and Report Generation

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Abstract / Executive Summary - Computer Aided Engineering (CAE) customization is crucial in modern product development, particularly in the fast-paced automotive industry. This study showcases a template-based load case creation and report generation framework built on Altair HyperWorks. This framework accelerates CAE-driven product development by capturing customer-specific processes in XML templates. These templates serve as inputs for batch and graphical user interface load case creation and report generation. The use of templates fosters flexibility and reusability. Developed using Tcl and Tk programming and HyperWorks APIs, this framework significantly reduces custom solution development time by 30 percent and overall load case setup and report generation time by 80 percent. Thus, increasing the efficiency of product life cycles.

Keywords - Altair HyperWorks, Process automation, Tcl and Tk, XML template.

I. INTRODUCTION

In the automotive industry, ensuring the validity of Computer-Aided Design (CAD) models through Computer-Aided Engineering (CAE) is essential but time taking. This process encompasses intricate designs, multiple test cases, and thousands of components, demanding significant manual labor from CAE engineers. The major manual tasks involved are the creation of loads & boundary conditions, the preparation of Design Verification Process (DVP) decks, post-processing, and creation of reports based on the results. Most of the steps involved in these tasks are repetitive and defined. This situation called for a solution to help the customer define a process capturing automation as well as the development of a framework to help in future automation.

Our team has devised a comprehensive solution to address the key challenges. This solution consists of two main stages:

1. Automation of Key CAE Steps: We have automated essential CAE processes, resulting in an impressive 80% reduction in time and effort required for the design verification process. This automation streamlines tasks, making them more efficient.
2. XML-Based Template Tool: Additionally, we have developed an XML-based template tool, simplifying the creation of new automation. This tool enhances the adaptability and scalability of our solution, enabling faster development of customized processes for specific needs.

It's a known fact that any CAE automated solution for load case setup and report generation will drastically reduce the CAE driven product development time. However, capturing all the customer specific processes for multiple load cases and its analysis reports and developing these many custom solutions involves tremendous amount of development time. Hence an approach to automate the loadcase setup and reduce the development time can be beneficial.

In this paper, we would like to present a generic template-based framework that not only reduces the time to develop automated load case setup

and report generation solutions, but also captures and stores the refined input parameters with respect to each load case and systems and reports. Each of these parameters can be stored as an XML template and reused. The templates thus created can be used to create and populate the graphical user interface with custom-specific information or can be used in batch mode to fully automate the load case creation to report generation.

As a part of the solution, we have taken a few NVH and durability load cases and the corresponding report generation. A detailed study on time reduction both from the developer and end-user perspective is depicted in this paper.

II. METHODOLOGY

The methodology for CAE validation in the automotive industry is a structured process aimed at ensuring the accuracy and reliability of design models. This approach spans from the initial selection of a meshed model to the generation of comprehensive reports detailing the analysis outcomes.

The methodology described is highly versatile, capable of accommodating a wide range of test scenarios conducted at both the full vehicle and assembly levels, with a primary focus on assessing NVH (Noise, Vibration, and Harshness) and durability analyses. In this process, the CAE engineer collaborates with multiple decks, each prepared to test various operating conditions of the vehicle. The initial decision-making step involves the user selecting the analysis type and design verification test for model preparation. Following this, CAD parts for the assembly are imported and meticulously assembled using connectors. Subsequently, loads and boundary conditions are applied to the system, and the decks are exported for solving. The exported decks undergo a solving process and are post-processed to provide the user with a comprehensive understanding of the product's behaviour. This rigorous sequence of steps is iterated numerous times to ensure the thorough validation of design verification tests before proceeding with product manufacturing. These are the streamlined process followed by many automobile companies. As shown in the below diagram, a general model building to report generation for any simulation involves, importing CAD (from PLM system), cleanup, defeature, meshing, creating connections, apply boundary conditions, job submission, post process the result and generate report.

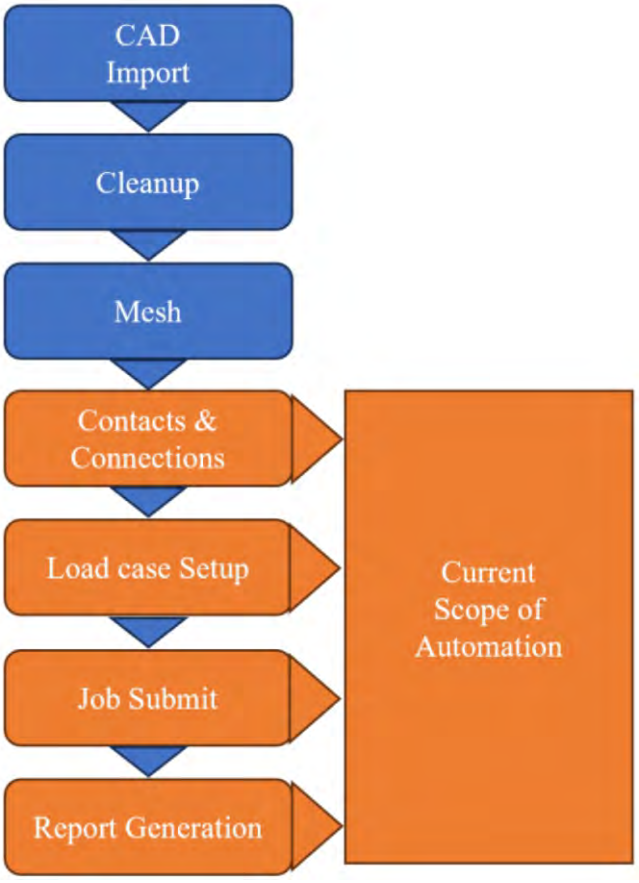

Figure 1:General model building process.

Our study reveals that, after a meshing process, using a standard process of node and element numbering or grouping important elements and nodes, the further steps of DVP generation can be automated. And this will enable tons of time saving. As suggested in the above picture the main focus of this paper is to ease the load case setup to report generation through automation, for which a XML based template approach as the title of the paper indicates is used.

The proposed methodology outlines a systematic approach to automate crucial steps within the current scope of the Computer-Aided Engineering

(CAE) workflow. It initiates with the creation of a specialized XML template, specifically tailored for the Design Verification Process (DVP) of the examined subsystem. This XML template serves as a foundational framework, encompassing options and automated selections crucial for subsequent phases of deck and report creation. The XML creation process, considered a preparatory and passive step, lays the groundwork for the ensuing active automation steps. The active automation process involves deck preparation, including the automatic import of parts, creation of connections, and contacts, as well as load case setup and validation checks. Essential selections within this tool are made, ensuring the readiness of a solver-ready deck. Following deck export, the solver run can be submitted either locally or on a server. Post-solver run, result files are utilized to generate standard reports, featuring crucial sections for design verification. The active automation approach significantly diminishes manual intervention in the CAE validation process, streamlining tasks from FE model preparation to the creation of detailed, standardized reports. The XML template functions as a central element, guiding and automating selections across these stages, thereby contributing to an overall more efficient and standardized design verification process.

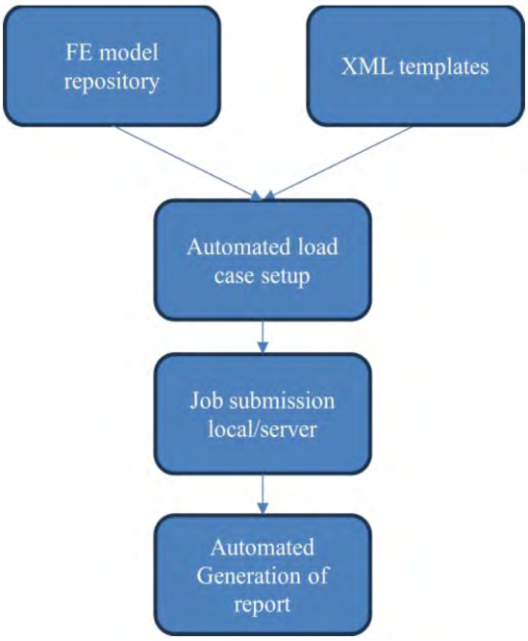

Figure 2: Solution workflow diagram.

A. FE Model Repository

The Part browser feature in HyperMesh provides a hierarchical view of the FE model and allows the users to organize and manage various assemblies, components, and analysis types efficiently. It enables the import, connection and selection of mesh representation files based on the analysis type being performed. The solver deck corresponding to the analysis under study is identified and auto loaded. By automatically identifying and loading the solver deck files corresponding to analysis (NVH, Durability etc.) being studied, the tool accelerated the model building process, saving valuable time and effort. The connections between the assemblies are established based on the node tags defined by the user. The model prepared is exported and later used for the loadcase setup. The part browser capability along with automations enhances efficiency and productivity of the entire finite element modelling workflow. The workflow developed uses the Part browser capabilities for storing the NVH and durability model representations and thereby using appropriate FE model for respective loadcase setup.

B. XML Template

This section describes XML template architecture. This template is capable of handling both graphical user actions and functionality actions. The XML template has 3 main sections. The Main section, category section and parameter section. The high-level section information is provided below:

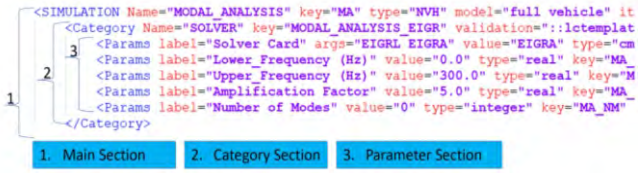

Figure 2: Solution workflow diagram.

The graphical user interface is built on top of property area widget of HyperWorks. The property area widget is populated by using the information from template. There are various graphical widget and control options provided in this template such entry widget for single entry, combo entries to provide multiple options, table widget to provide

columns of data. Also, in order to control the view with respect to a given input, a visibility option is provided. An example of the visibility option is provided below:

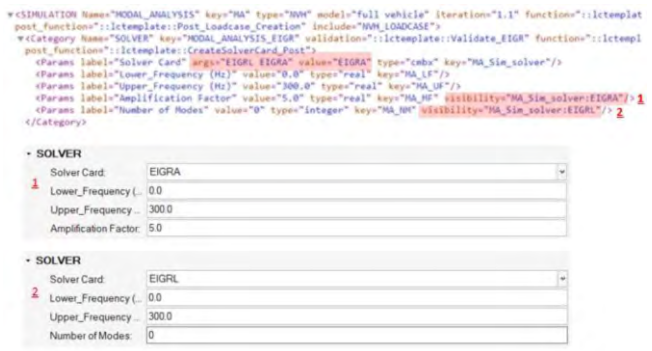

Figure 4: Controlling visibility options using template.

Another advantage of this template is the table widget, this option is very handy when it comes to providing more inputs. This table widget is also designed in such a way that any entity selection is made easier. The user needs to only provide the type of entity to be shown in the table column, an example is shown below:

Figure 5: Table widget option through template.

The contents can be prepopulated in the table through CSV.As an inbuilt feature of this template, there are few quick access commands provided for the ease of developers, such getting a value of parameter, get the contents of the table etc. This capability makes the development of solutions using this framework faster and easier. An example of an xml template to create modal analysis load case and its corresponding report is shown in this section. As depicted in figure 6, xml template captures all the relevant steps for setting up modal analysis and to generate respective analysis reports. This framework has enough inbuilt commands to query, modify and execute respective tailored commands for load case setup and report generation. Multiple templates with respect to the analysis and system type can be created and stored in a database.

Figure 6: XML template file for Modal analysis.

The XML template has been designed and architected in such a way that it is easily configurable. The template has been carefully architected, and options to perform pre, current and post actions are part of this framework. This makes the code development also modular, and the developer only needs to concentrate on developing tasks at macro level and not at solution level.

C. Automated Loadcase Setup

This template-based load case setup solution captures all the relevant steps to set up load case, thus standardizing the process. The process thus captured can be used by any user irrespective of their experience. As an example, to describe the load case setup, a typical modal analysis of an exhaust system is shown in this paper. The XML shown in the previous section is used as a template and the generated graphical user interface is shown below:

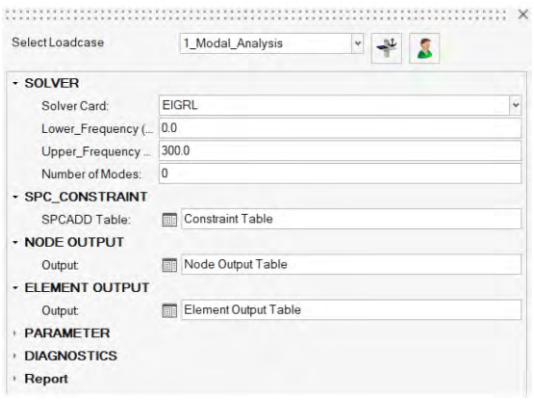

Figure 7: Graphical interface generated through the XML template for Modal Analysis

The parameters thus provided are read and applied on the model to complete the load case

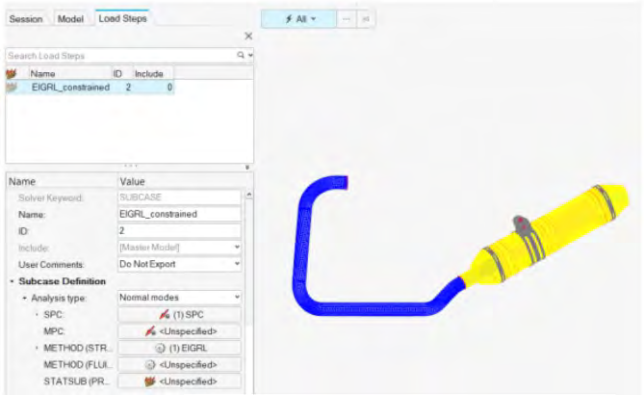

Figure 8: Modal Analysis deck generated through custom framework using XML template.

setup.

D. Job Submission

This template-based solution supports solving of the deck thus generated through Optistruct. The deck can be solved through a local installation or server installation. A separate section in the XML template to provide the solver details is provided.

E. Report Tool

The report generation of the analysis thus performed can also be automated using this framework. The required results to be generated on the custom power point template can be configured in this template. As an example, the result extraction options under the modal analysis are shown

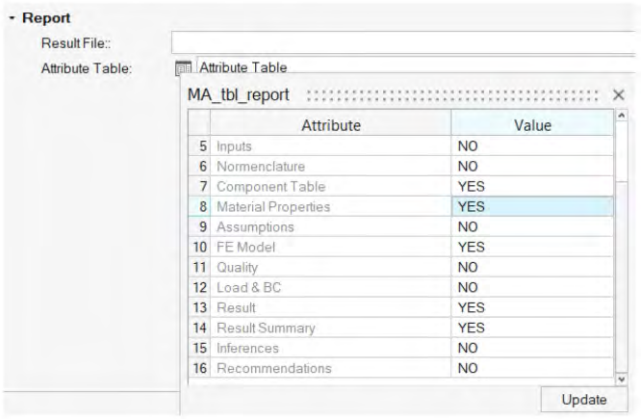

Figure 9: Report generation options.

below:

The report thus generated will be captured in the

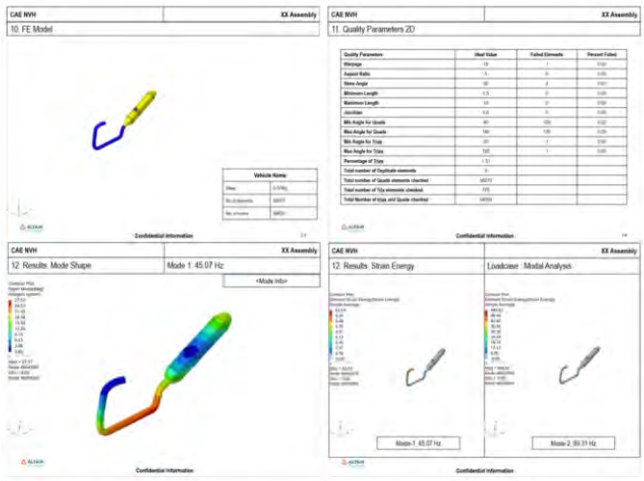

Figure 10:Sample report slides.

customer specific template as shown below:

The typical report contents include objective, model summary, material summary, contact information, model quality summary, displacement results, stress results, strain results, mode shape results, results summary, conclusion etc. The above-mentioned contents are included in the DVP reports based on the use case. Each report content is a module that can be captured in the XML templates. The report content functionalities when used along with the templates significantly reduces the development efforts.

III. RESULTS

The template-based automation solution developed for automotive customer proved to be highly effective in enhancing the efficiency of the load case and report creation processes. This innovative approach, which leveraged XML-based templates, resulted in substantial benefits for the project.

The implementation of XML-based templates brought about a transformation in the workflow, shifting the focus from coding-intensive tasks to file-based editing. This transition had a profound impact on the following aspects:

Graphical User Interface (GUI): The XML-based templates simplified the user interface and interaction, reducing the need for extensive coding. As a result, developers could perform tasks with greater ease and speed.

Load Case Configuration: With the template automation, configuring load cases became a streamlined, file-based process. This approach not only improved efficiency but also reduced the likelihood of errors in load case setup.

Report Generation: The report creation process was significantly optimized using XML-based templates. Developers were able to generate comprehensive reports with lesser manual effort and coding, resulting in more consistent and error-free documentation.

One of the most notable achievements of the XML-based template automation was the substantial reduction in development time for new Design Verification Process (DVPs). In comparing projects before and after the implementation of this solution, we observed a remarkable 30% reduction in the time required to create and execute DVP tools.

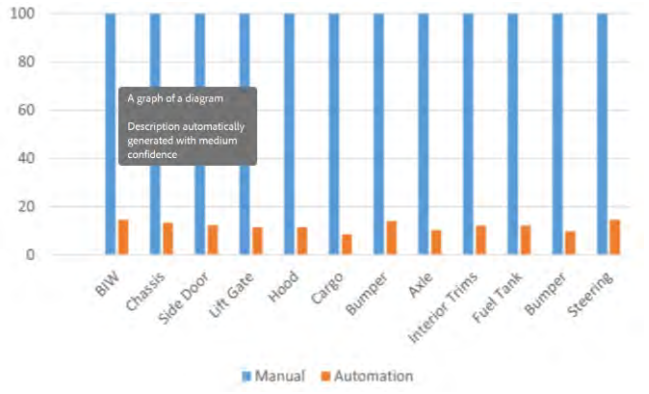

Figure 11: Automation efficiency results

Across the board, automation processes have significantly reduced manual assembly times, resulting in substantial time savings for each component. The greatest time savings were achieved in the "Cargo" assembly, where automation reduced the time required by approximately 91.38%. Other components, such as "Chassis," "Side Door," "Lift Gate," and "Hood," also saw substantial time savings, exceeding 85%. The automation process for "Bumper" achieved a notable 90.24% time savings, further highlighting the effectiveness of automation in assembly operations. These results underscore the tangible benefits of implementing automation in our assembly processes, leading to increased efficiency and productivity across various components of our production line. This time savings had a direct and positive impact on project timelines and overall productivity. Engineers could now focus more on the critical aspects of design verification and analysis, leading to quicker project iterations and a more efficient product development process.

In summary, the XML-based template automation solution not only simplified complex tasks but also delivered substantial time and efficiency gains, making it a valuable asset for our automotive customer's engineering and analysis processes.

IV. CONCLUSION

Expanding the proposed solution to accommodate additional analysis types, such as crash analysis, involves a streamlined effort due to the foundational functions already established for various analysis deck and report creation processes. The existing functions can be adapted for crash analysis by modifying the script to incorporate crash-specific parameters, load cases, and validation checks. Drawing on experience gained from the initial implementation, the XML template is either modified or a new one is created specifically tailored for crash analysis. This experience-based approach in XML template development aims for efficiency and reusability, leveraging the foundational structure of the original template and anticipating commonalities between different analysis types. This adaptation process targets a reduction of approximately 30% in development effort compared to the initial implementation, ensuring an efficient and scalable solution for diverse Computer-Aided Engineering (CAE) analyses.

The below workflow shows an example of a pendulum crash load case setup. A GUI thus generated using the XML template is shown in figure 12. This concludes that any load case setup with a proper process standardization can be quickly automated with the proposed template-based approach.

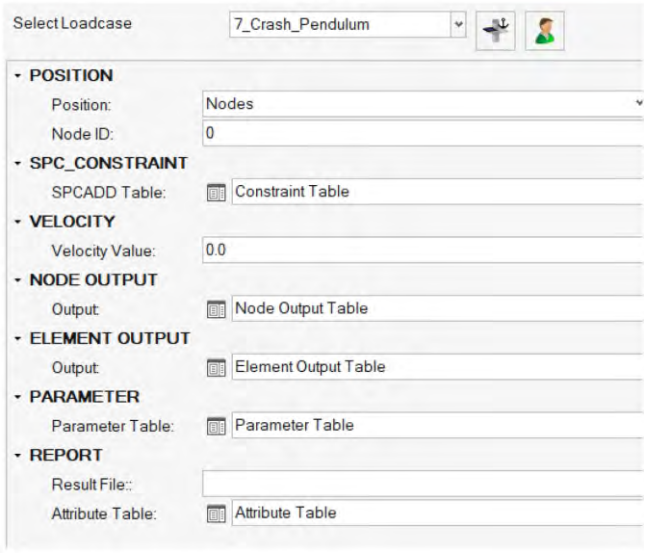

Figure 5 Converting design tokens to Manufacturing tokens

Figure 13:Template for the above GUI.

As depicted in the above sections there were significant savings in the development of solutions and the DVP process using this template-based solution. This concept can be further extended to more DVPs such as Crash and other verticals. This can be easily integrated into any PLM system.

V. ACKNOWLEDGMENT

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Also, we acknowledge the support provided by our company, Altair Engineering Pvt Ltd. Their generosity made it possible for us to access essential resources and materials for the research.

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Simplifying Parametric Analysis Across Product Lines

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Abstract - The purpose of this study is to establish a process for enabling the creation of alternate variants (100%) and performing parametric analysis on portfolios (150%). This process shall help system engineers do trade studies, understand the usability of various elements, and reduce calculation parameters for individual variants reducing engineering efforts.

For instance, a large automotive company produces tens of thousands of variants for a single portfolio (Product line). While performing parametric analysis, a parametric equation must be captured to calculate "total cost" as a parameter for a specific variant. That means in case there are 70 variants in the portfolio, the user will have to capture 70 different parametric equations to complete the parametric analysis of the portfolio (150% model).

In our research, we employed the Systems Modeling Language (SysML) to execute Model-Based Product Line Engineering (MBPLE) and conducted parametric analysis, effectively addressing the challenges presented. To optimize our approach, we leveraged the 'roll-up pattern', which allowed us to deconstruct system-level parameters, such as total cost, into multiple parameters for sub-systems (e.g., Cost of part 1, part 2), thereby reducing the overall number of parametric equations required for parameter calculation. Furthermore, within the domain of variant modeling, we adopted a comprehensive strategy, capturing 150% of Requirements, Functional architecture, and Logical architecture, and verifying these requirements rigorously. By consolidating all variants within a single model, our variant modeling approach streamlined the modeling process. Additionally, the parameter analysis for the 150% model facilitated the calculation of critical parameters such as cost, mass, power, and more. This, in turn, led to a reduction in modeling efforts and an enhancement in reusability, offering a more efficient and effective solution for our engineering challenges.

Keywords - Model-Based Product Line Engineering (MBPLE), Rollup Pattern and SysML.

I. INTRODUCTION

Product Line Engineering (PLE) stands as a paramount methodology for expediting the introduction of new products to the market. PLE represents an approach to efficiently engineer a collection of interconnected products, harnessing the benefits of shared characteristics while effectively overseeing their distinctions. In essence, PLE treats the product line portfolio as a unified entity comprising numerous akin yet distinct products. It is a method for effectively managing variances across a variety of related products while maximizing their commonalities. Planning, develo-ping, distributing, deploying, maintaining, and even retiring products are all included in PLE [1].

PLE views the product line portfolio as a single entity that needs to be controlled rather than a large number of closely related but distinct goods. Businesses can reduce labor, time, and quality by utilizing product commonality while controlling variation. This makes it possible for a uniform, automated approach to be used throughout the full life cycle, including tool ecosystems, software, electrical, and mechanical domains, engineering and operations disciplines, and so on [1].

Model-Based System Engineering (MBSE) and PLE are combined to form MBPLE. The user may model all of the versions' requirements, functional architecture, logical architecture, and physical architecture in one place. Requirement engineers, architecture engineers, V&V engineers, and model engineers can lessen the effort by using the MBPLE method. MBPLE is applicable for the duration of the product's lifecycle [2].

A general-purpose modeling language for systems engineering applications is the systems modeling language (SysML). It supports a wide range of systems and systems-of-systems (SOS) in terms of definition, analysis, design, verification, and validation.

One of the most frequent use cases in systems engineering is rollup calculations. Based on the individual values of each component in the model, system modelers aim to determine the total mass, cost, power, or another system dimension. The value may be propagated up a hierarchy of components by the pattern in a recursive manner [3].

The creation of new elements and time reusability is a challenge faced by system engineers while modeling different variants of a product in independent models. Using the MBPLE method for variant modeling and calculating the parameters of the variant more parametric diagrams for all the stages of the hierarchy were created. It is difficult to combine all the parametric diagrams while calculating the parameter at the top layer of the hierarchy. Hence rollup pattern in the top layer of the hierarchy was used.

In this paper, we introduce the concept of a '150% model,' which entails the comprehensive capture of diverse variant information, including requirements, functional architecture, logical architecture, physical architecture, and parametric analysis, all within a single model. Conversely, a '100% model' focuses on the specific details of an individual variant. The term 'portfolio model' serves as a general reference for the overarching 150% model framework. Our experimental system of interest (SOI) is the bicycle, with two distinct variant types: the basic bicycle and the premium bicycle.

We recommend the application of MBPLE and Rollup patterns for parametric analysis. This enables us to incorporate several variants into a single model and compare more than two models at once to identify the similarities and differences between the variants.

II. METHODOLOGY

A. Steps to Implement the Proposed Process

We used CAMEO Systems Modeler (SysML tool) with the Product Line Engineering plugin (for MBPLE) to demonstrate this process. Steps to follow the recommendations and implementation plan are shown figure below (Figure 1).

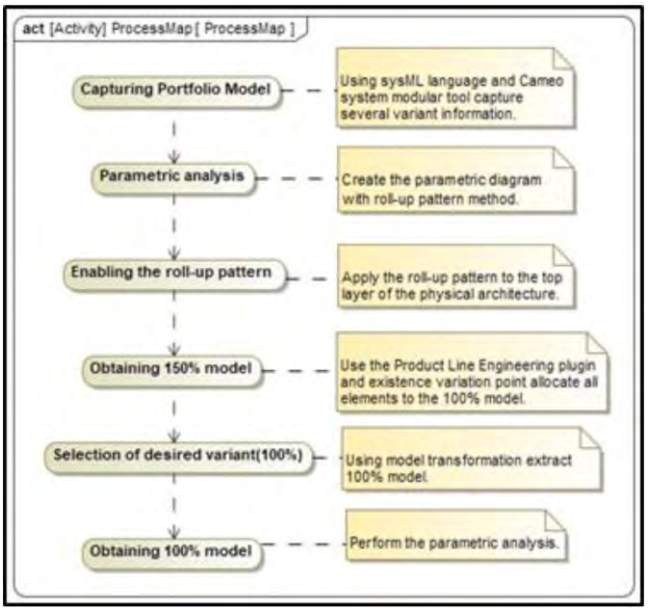


Figure 1: Implementation steps

PRE-REQUISITES

To understand the proposed process, basic knowledge of the following is needed.

- Language -- SysML language
- Tool -- Cameo System Modeler
- Tool plugin -- Product Line Engineering (MBPLE)
- Tool plugin -- Cameo Simulation Toolkit plugin

IMPLEMENTATION STEPS

1. Capturing Portfolio Model
2. Parametric analysis
3. Enabling the roll-up pattern
4. Obtaining 150% model
5. Selection of Desired Variant (100%)
6. Obtaining 100% model

1) Capturing Portfolio Model

All the requirements were captured in the Cameo requirements table. For this SOI, only the requirements (Figure 2 part 1) were captured; however, in reality, systems engineers will need to capture all the applicable system requirements.

#	Name	Text
1	1 Premium tyre	Premium cycle shall have set of two premium tyre
2	2 Premium pedal	Premium cycle shall have two fancy pedal
3	3 Basic pedal	Basic cycle shall have basic pedal
4	4 Basic tyre	Basic cycle shall have set of two basic tyre
5	5 Cycle frame	Cycle shall have the frame

1

#	Name	Text
1	1 Premium tyre	Premium cycle shall have set of two premium tyre
2	2 Premium pedal	Premium cycle shall have two fancy pedal
3	5 Cycle frame	Cycle shall have the frame

1a

#	Name	Text
1	1 Premium tyre	Premium cycle shall have set of two premium tyre
2	2 Premium pedal	Premium cycle shall have two fancy pedal
3	3 Basic pedal	Basic cycle shall have basic pedal
4	4 Basic tyre	Basic cycle shall have set of two basic tyre
5	5 Cycle frame	Cycle shall have the frame

2

Figure 2: Requirements

In the portfolio physical architecture, we captured bicycle parts such as the basic tyre, premium tyre, basic pedal, fancy pedal, and frame (Figure 3 part 1) utilizing the block definition diagram (BDD) for the 150% model.

Applications of parametric analysis include calculating parameter values, such as cost, mass, and others, and verifying the quantitative requirements.

For the premium bicycle, we capture the individual cost of the frame, premium tyre, and fancy pedal to calculate the total cost (Figure 5 part 1a).

Similarly, for the basic bicycle, we capture the individual cost of the frame, basic tyre, and basic pedal to calculate the total cost (Figure 4 part 1b).

2) Parametric Analysis

If the configuration requires multiple versions for a complex system, the system engineers would need to define several parameters and subsequently several parametric diagrams. With the usage of the Rollup pattern, the complexity is reduced by having a common parametric diagram for a baseline system portfolio (150%). Shown below (Figure 5 Part 2), is how we used a common parametric diagram for a bicycle and rolled up the diagrams for the basic and premium variants. In the parametric analysis, the parametric output value goes to the input of the rollup pattern.

#	Name	cost : Real	totalCost : Real
1	cycle	0	265
2	cycle.frame	45	45
3	cycle.basic Pedal	54	54
4	cycle.basic Tyre[1]	11	11
5	cycle.basic Tyre[2]	45	45
6	cycle.fancy Pedal	54	54
7	cycle.premium Tyre[1]	85	85
8	cycle.premium Tyre[2]	33	33

Figure 4: Portfolio instance table

Using the parametric diagram an instance table was created as shown above figure (Figure 4).

As shown in Figure 4, we captured multiple variants in one model and we performed the parametric calculation. Using the roll-up pattern method, system engineers can avoid the creation of additional parametric equations/diagrams for multiple variants.

3) Enabling the roll-up pattern

For complex systems, parametric analysis is challenging because of the multiple hierarchy levels. Using the roll-up pattern methodology on the top level of the physical architecture. The pattern will recursively propagate the total of the values of those attributes up the hierarchy of the architecture.

4) Obtaining 150% model

We allocated all elements 150% to several 100% configurations using the existence variation point (Figure 7). The existence variation points provides a mechanism for modeling flexibility and

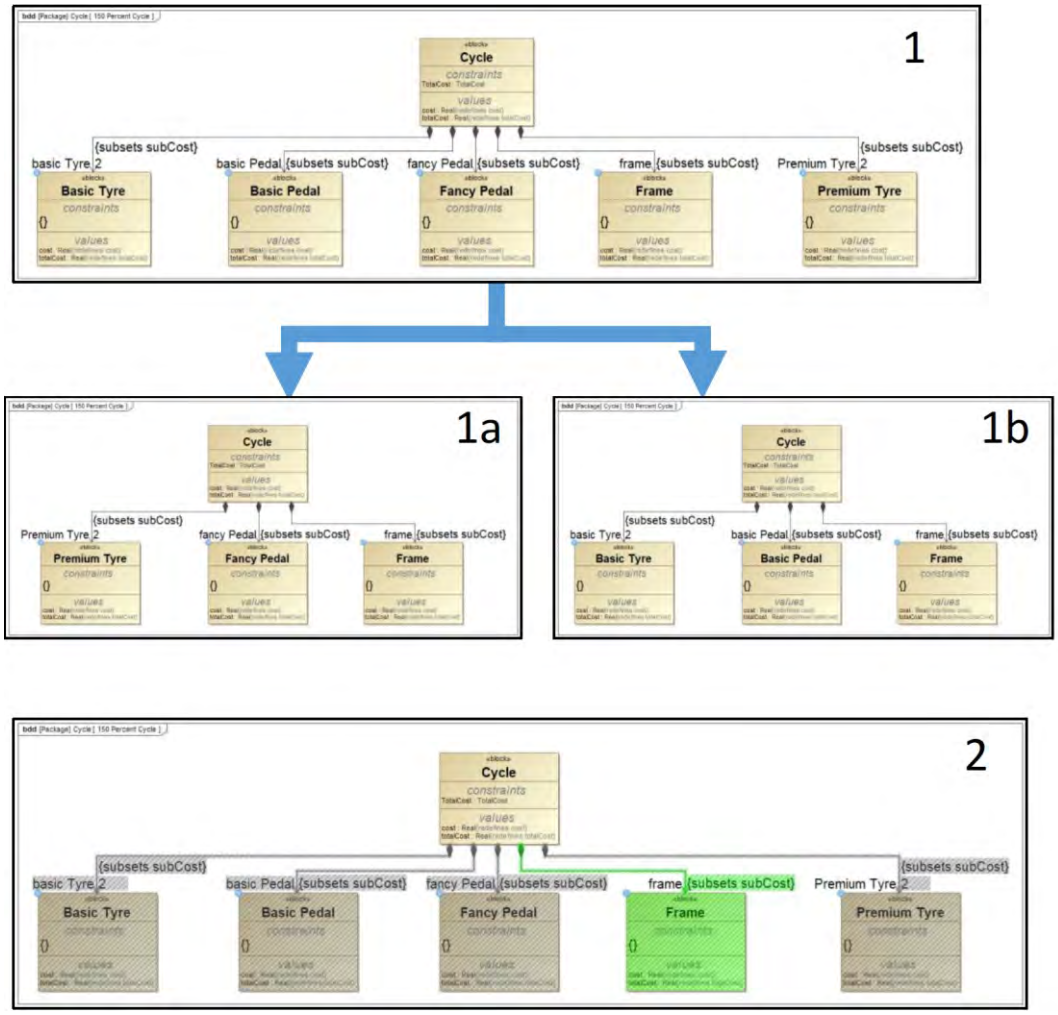
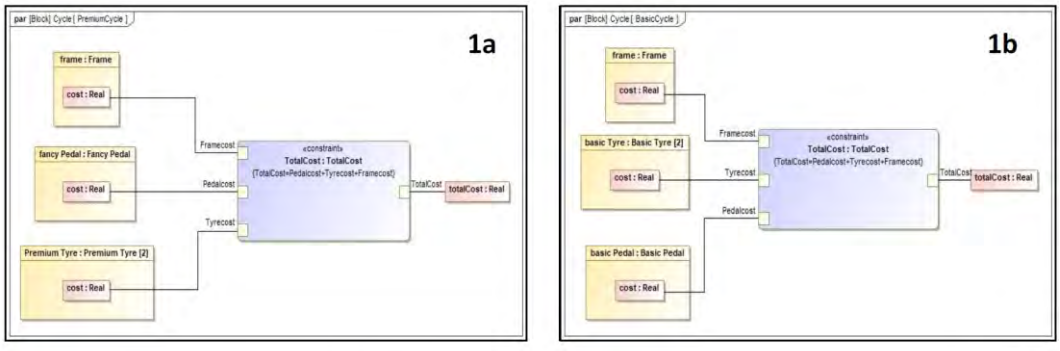


Figure 3: Physical architecture



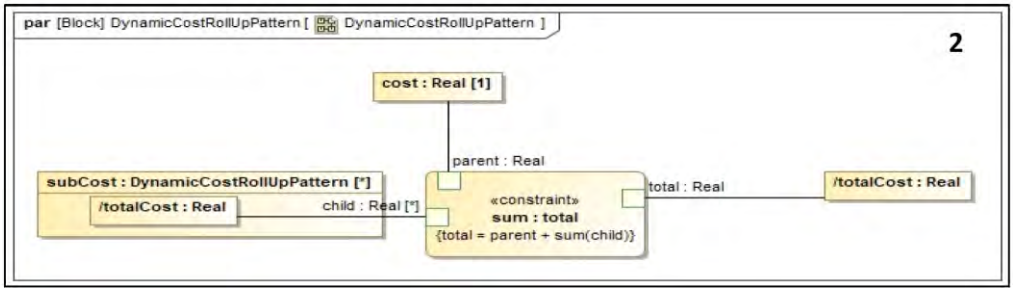


Figure 5: Parametric analysis

adaptability, allowing you to capture and manage variability within your system or software throughout its lifecycle. This is particularly valuable in scenarios where customization, product line engineering, or handling different configurations are essential.

#	Name	Constrained Element
1	{} BasicPedal	Basic Pedal R 3 Basic pedal
2	{} BasicTyre	Basic Tyre R 4 Basic tyre
3	{} FancyPedal	Fancy Pedal R 2 Premium pedal
4	{} Frame	Frame R 5 Cycle frame
5	{} PremiumTyre	Premium Tyre R 1 Premium tyre

Figure 6: Allocation of elements for 100% configuration

5) Selection of Desired Variant (100%)

Using model transformation a systems engineer can extract the 100% configured model and compare more than one variant to find similarities or differences between the elements.

III. RESULTS AND DISCUSSION

In our study, we have employed a preview feature (Figure 7) within the portfolio architecture to visually present the outcomes and facilitate the discussion of commonalities and differences among elements across multiple variants. As demonstrated in the subsequent figure (Figure 2 part 2), we represent common elements in green and highlight uncommon in gray. In the following sections, we will delve into the results and engage in a comprehensive discussion of our findings.

Using the preview feature we can see the 100% requirement for the selected (premium) variant as shown in the below figure (Figure 2 part 1a).

Using the model transformation feature, we extracted the premium bicycle elements such as frame, premium tyre, and fancy pedal as shown in the figure above (Figure 3 part 1a).

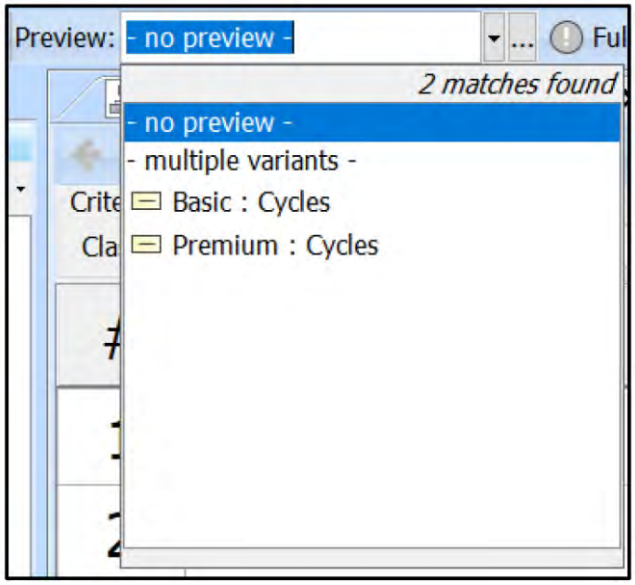


Figure 7: Preview selection

Using the model transformation feature, we extracted the basic bicycle elements such as the frame, basic tyre, and basic pedal as shown in the figure above (Figure 3 part 1b).

Similarly, in architecture, we showed the commonality and differences of the elements for multiple variants. In the figure above (Figure 3 part2) green color represents the common element and gray color represents the differences of the variants.

Using IBD (Internal Block Diagram), the system engineer can create a simple validation check to validate the selected structure.

In the figure below we selected a basic pedal for the premium bicycle variant, which is shown in red color (Figure 8). The system engineer can identify the possible structural element.

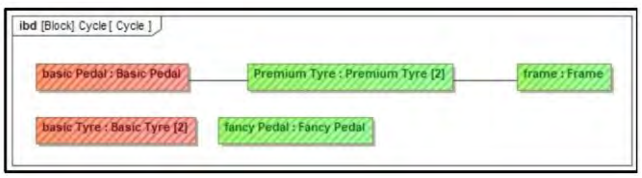


Figure 8: Validation of selected structure using IBD

After extracting the premium bicycle model from the portfolio model, without creating a new parametric diagram, we can perform the

parametric analysis using the portfolio instance table (Figure 9) reducing the engineer's work

#	Name	cost : Real	totalCost : Real
1	cycle	0	184
2	cycle.frame	45	45
3	cycle.fancy Pedal	54	54
4	cycle.premium Tyre[1]	85	85
5	cycle.premium Tyre[2]	33	33

Figure 9: Instance table for premium bicycle

IV. CONCLUSION

This paper demonstrates how by using the MBPLE method, the System Engineer (SE) can capture the model's 150% requirement, architecture, parameters, etc., and define the overall scope of desired complex SOIs such as automotive, aerospace, industrial, etc. Performing parametric analysis using A parametric diagram with the roll-up pattern, the SE can calculate the values of THE required parameters of the system and verify the quantitative requirement. This will simplify the development process by reducing the required engineering effort for parametric analysis of the complex system. As an example, a significant reduction of parametric diagrams (1 diagram in place of 10) can be performed using the roll-up pattern.

In the research on the bicycle example, we reduced the engineer's effort marginally by using MBPLE and the roll-up method. The benefit of these efforts can be higher for a complex system that has multiple variants.

Capturing all variant elements in one model is extremely effective for comparing more than one variant to find the differences and commonalities between them. This also results in increased reusability of the elements and THEIR attributes (such as KPIs, TPMs, etc.). For instance, in the automotive industry, it will drastically reduce the time to market for new products.

V. REFERENCES

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[2] Model-Based Product Line Engineering with Genetic Algorithms for Automated Component Selection-- Habibi Husain Arifin, Ho Kit Robert Ong, Jie Dai, Wu Daphne, and Nasis Chimplee

[3] https://docs.nomagic.com/display/SYSMLP2022xR2/Rollup+Pattern+Wizard

Assessment of Bird Impact and Foreign Object Damage on Infrared Search & Track System and Airframe of Modern Combat Aircraft

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Abstract - In this paper, a method to design bird-strike- resistant aircraft structures is presented and illustrated through an example. The focus is on bird strike analysis & simulations and modification of structure for impact resistance based on analysis results. The explicit finite element software LSDYNA from Ansys is used to perform analysis. Smooth Particle Hydrodynamics method is coupled with the Finite Element method and used to simulate the interaction between bird and the target aircraft structure. Details of the comprehensive analysis performed to evaluate Foreign Object Damage caused by bird impact on the Infrared Search and Track system of modern fighter aircraft are presented. Secondary damage assessment is also carried out to evaluate effects on adjacent windshield and frame structure. Aircraft structure modification has been carried out by a series of design iterations to develop bird impact resistance design.

Keywords - Bird Impact, FOD, IRST, Safe impact speed, SPH, ALE

I. INTRODUCTION

Bird strike has long been a significant threat to aviation safety. The first bird strike dated back to 7th September, 1905, recorded by the Wright brothers. The United States Air Force reported 13427 bird/wildlife strikes to aircraft worldwide between 1989 and 1993, and estimated the damage to civilian and military aircraft to cost hundreds of millions of dollars every year [1]. Most bird strikes occurred when aircraft was at low altitude - during the take- off and landing phases of flight [6]. The most vulnerable components to bird strikes are wind shield, Infrared Search and Track (IRST) system, aircraft nose, air-intake, engine and wing leading edge. To ensure flight safety, aviation regulations require a certain level of bird strike resistance for these critical components.

Most early research on bird strikes was experimental based. In bird strike experiments on stiff plates, it was found that peak pressure generated during impact was proportional to square of the impact velocity, regardless of the bird's geometry [1]. Although bird strike experiments provide a direct method to study resistance of components to bird strikes, with the rapid development of computer technology and finite element methods, numerical simulations provide an alternate way to study resistance of components to bird strikes. Also, many design iterations can be performed in less time and cost. Traditionally bird was modeled using Lagrangian, Arbitrary Lagrangian Eulerian (ALE) methods. More recently Smoothed Particle Hydrodynamics (SPH) methods are being used to simulate bird collision events and estimate pressure distribution on the target. Current research on bird strike simulation mainly focuses on the following three aspects [1]:

1) A constitutive model for bird. A bird's body is not a homogeneous medium. It includes bones, flesh, feathers, etc., so there is a need to create an equivalent model. Additionally, birds exhibit different mechanical behavior at different impact velocities. For low-velocity impacts, the bird can be considered an elastoplastic body, but for high-speed impacts, its behavior resembles that of a liquid.

2) Mechanical behavior of aerospace materials under high strain rates. Bird strike is a highly transient event that lasts just a few milliseconds. As a result, materials affected by bird strikes would experience moderate to high strain rates. For many materials, the strain rate can have a significant impact on mechanical behavior, which in turn influences dynamic response of the structure.

3) Numerical techniques to simulate the bird strike process. Three methods have been used to simulate dynamic response of aircraft structures under bird strike: uncoupled method, coupled method and SPH method. In this study, SPH method is considered which is a meshless method and capable of solving large-deformation and nonlinear dynamic problems.

This paper presents a comprehensive analysis of foreign object damage (FOD) caused by bird impact on IRST system of a generic combat aircraft (Fig. 1(a)). The IRST system is a crucial component in modern aerial combat providing enhanced situational awareness through passive infrared detection and tracking capabilities. However, its vulnerability to potential damage from external elements such as birds, warrants a thorough investigation to assess its operational resilience and safety.

Various components of a typical IRST system are shown in Fig. 1(b). These include outer IRST dome, internal components like mirror, supporting kovar ring, and aluminium support and base structure secured with 13 bolts.

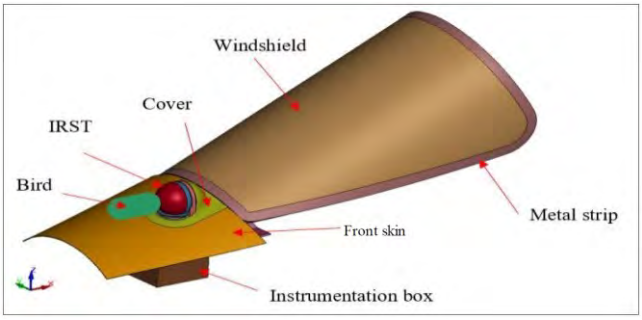


Fig. 2 Simple Change Management Process

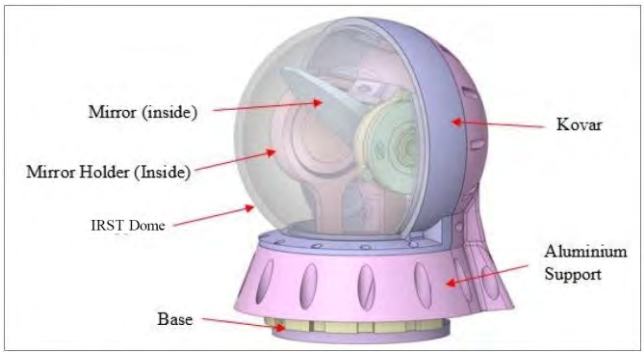


Fig. 1(b). IRSTcomponents

II. ANALYSIS

FOD risks in aircraft systems emphasize the importance of continuously assessing and improving design and materials used in critical components. A generic combat aircraft with IRST installed on front fuselage has been analyzed for following two bird impact loading levels:

CASE I: 1 kg bird at 850 kmph [2]

CASE II: 1.8 kg bird at 850 kmph: Rationalization of [3]

Critical bird impact location is at center of IRST dome. Post bird strike, extent of damage to IRST, its mounting and adjacent windshield structure has been assessed. Design modifications to airframe have been proposed where required. While IRST may incur damage, the objective is to ensure that airframe damage is minimal so as to enable safe landing post bird impact.

Further, safe impact speed for ensuring no damage to IRST for both cases (I & II) has been assessed by carrying out iterative studies by varying bird impact speed.

III. BIRD GEOMETRY

The variation of bird mass versus diameter is plotted in Fig. 2 [4]. Bird diameter was computed as 87 mm and 107 mm for 2.2 lb and 4 lb bird model respectively. Bird is modeled as a right circular cylinder with hemispherical ends (Fig.3a and 3b). An l/d ratio of ~2.35 has been adopted.

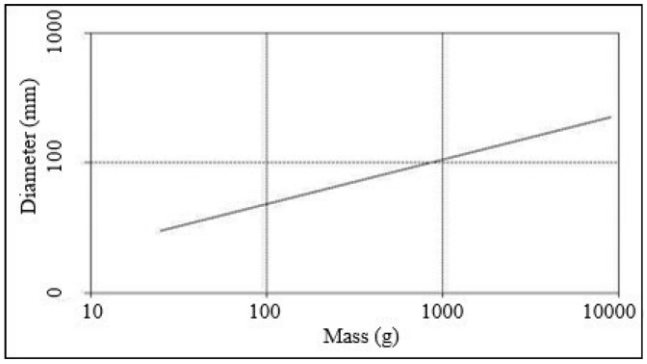


Fig.2. Bird mass Vs Bird diameter

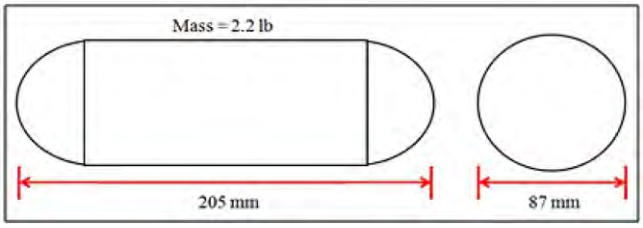


Fig.3(a). Geometry of 2.2 lb bird

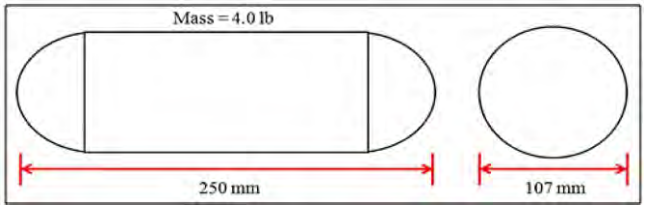


Fig.3(b). Geometry of 4 lb bird

IV. BIRD MESH

The bird has been modeled with SPH method, as implemented in ANSYS LSDyna solver. SPH is a meshless Lagrangian technique wherein the component is represented as a set of discrete interacting particles, which are independent from each other, being able to cover large deformations without the problem of mesh distortion. The SPH model for bird is generated as per geometry in Section-III and with 5mm spacing between nodes (Fig. 4).

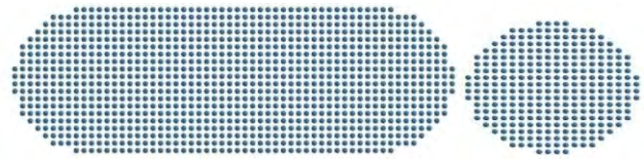


Fig.4. SPH mesh of bird

V. BIRD MATERIAL PROPERTIES

The variation of bird mass versus density [3] is plotted in Fig.5. Density for 4 lb and 2.2 lb bird is computed as 0.942 g/cc and 0.96 g/cc.

Following assumptions are made for carrying out bird strike analysis:

- The bird behaves as a fluid on impact.
- The pressure resulting from the bird impact is relatively constant at any point on the surface of the target (quasi-static fluid flow).

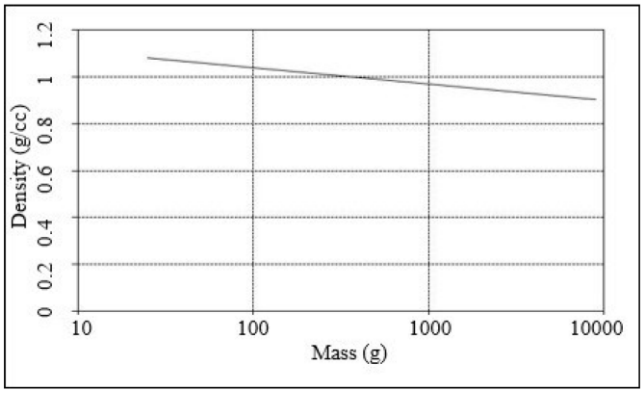


Fig.5. Relationship between bird mass and density

A hydro-dynamic material model has been assumed for the bird as it takes into account volumetric components of stress/strain and better suited at higher strain rates. It is computational model which used to simulate material behavior when subjected to fluid flow. The compressibility effect of the material is evaluated using the Polynomial Equation of State [5]-

$P = C0 + C1 + C2\ 2 + C3\ 3 + (C4 + C5 + C6\ 2)E$ (1)

P- Pressure (Pa)
C_0–C_6 - Coefficients of the polynomial equation
- Change in density during the impact
E - Internal energy (J)

VI. ANALYSIS RESULTS

Bird impact analysis setup completed as per Material Models (LS-Dyna Manual) [7] and results indicate that IRST dome suffers significant damage due to bird impact for both Case-I and Case-II.

Extent of damage to IRST parts and airframe is estimated and analysis results are presented.

A. CASE I : Analysis results

Analysis result shows that post bird hit, 89% of kinetic energy is transferred to the target. Resulting damage to target is shown in Fig. 6(a-d). Extensive damage is caused to IRST, while the windshield is not affected. However, windshield (WS) flange and vertical stiffener of WS forward arch undergo minor damage. Supporting Kovar ring of IRST does not rupture and strain contour plot is shown in Fig. 6(e). Axial and shear forces for 13 no.s base bolts are shown in Fig. 6(f) and (g).

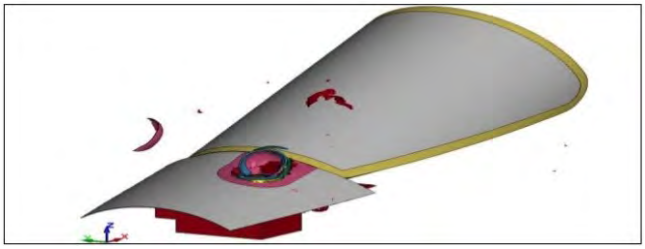


Fig. 6(a). Damage post bird hit

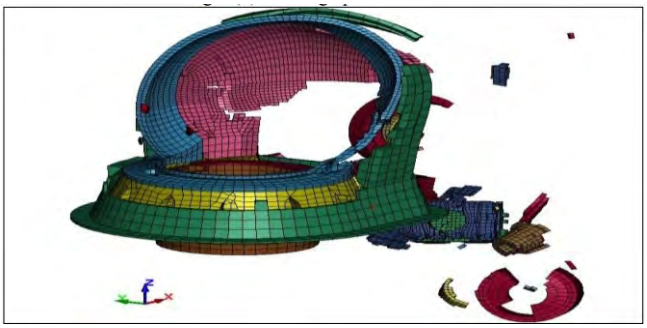


Fig. 6(b). IRST damage

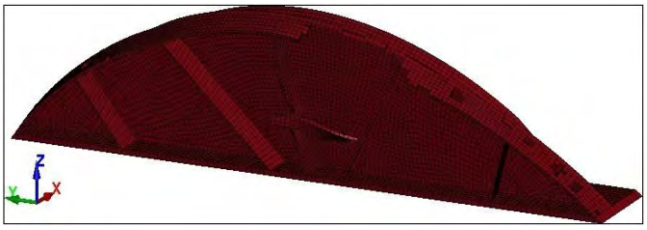


Fig. 6(c). Damage to WS forward arch

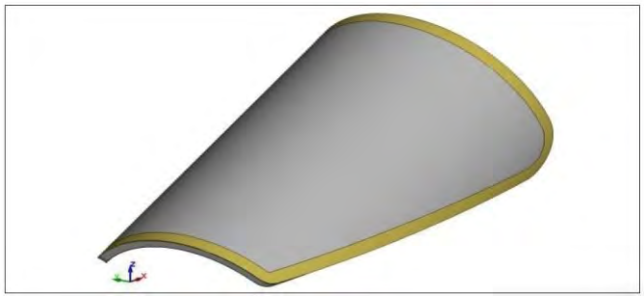


Fig. 6(d). Wind shield: no damage

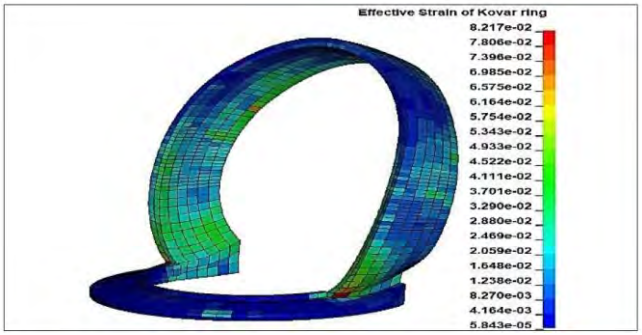


Fig. 6(e). Strain in Kovar ring

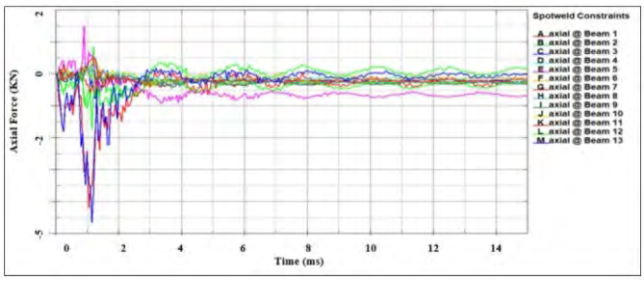


Fig. 6(f). Axial Forces on bolts: Case-I

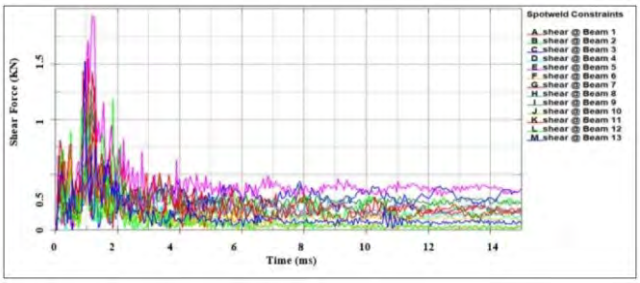
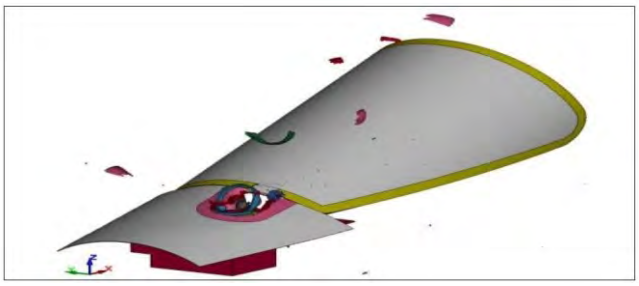


Fig. 6(g). Shear Force on bolts: Case-I

VII. CASE II : ANALYSIS RESULTS

Analytical predictions of damage post bird hit are shown in Fig. 7(a-d). The impact causes 93% of kinetic energy transfer to the target IRST and aircraft structures. Primary damage is caused by bird impact to IRST and is seen to be extensive. Secondary damage is caused by IRST parts impacting airframe structure. This results in local damage to metal strip on windshield edge and to windshield top layer which gets chipped. Further, flange, web and vertical stiffener of windshield forward arch also undergo rupture - approximate flange and web damage area is 25 mm x 125 mm and 75 mm x 100 mm respectively. Supporting Kovar ring does not rupture and strain contour plot is shown in Fig. 7(e). Axial and shear forces for 13 no.s base bolts are shown in Fig. 7(f) and (g).



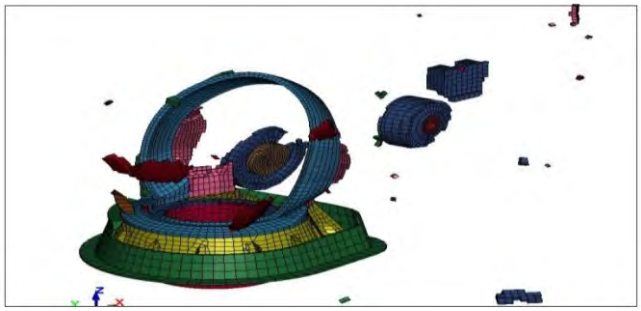


Fig. 7(b). IRST damage

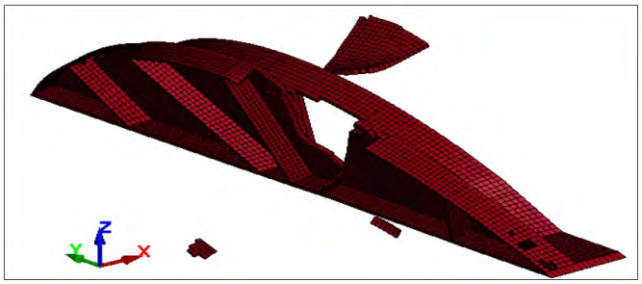


Fig. 7(c). Damage to WS forward arch

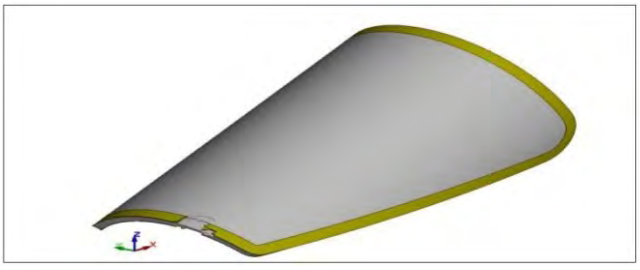


Fig. 7(d). Wind shield damage

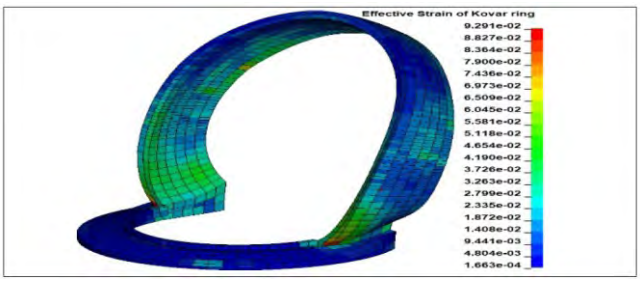


Fig. 7(d). Wind shield damage

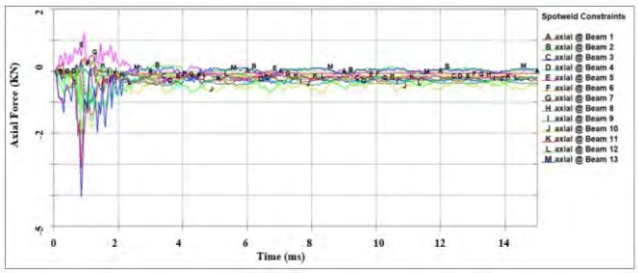


Fig. 7(f). Axial Forces on bolts

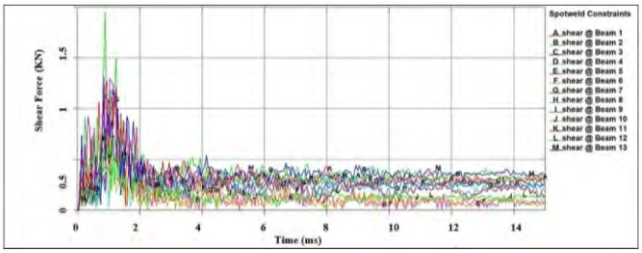


Fig. 7(g). Shear Force on bolts

Fig. 7. Analysis results: Case-II

VIII. PROPOSED DESIGN MODIFICATIONS

For CASE-II loading, it is seen that front flange and web of WS forward arch get ruptured which could lead to cockpit de-pressurization (Fig. 8). This has serious implications on pilot safety and continued mission operation.

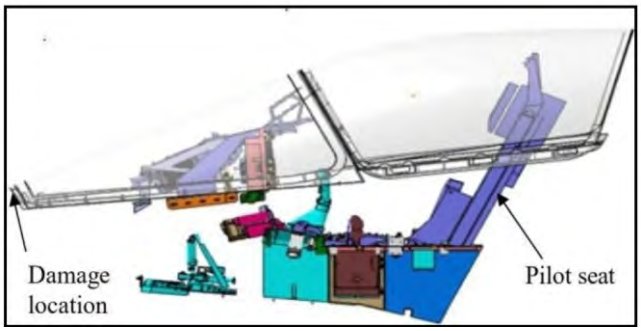


Fig. 8. WS forward arch and adjacent aircraft components

Further analysis iterations (I to III) described in sections A to C below were carried out to achieve an improved bird impact resistant design for WS forward arch by considering different material and thickness, while minimizing weight penalties. Three basic design principles generally employed to protect aircraft structures against bird strikes are listed in [1]. These include increased energy absorption, increased energy dissipation and

providing a multi-layered design for the target structure. Based on this, design iterations have been carried out as per flowchart in Fig.9.

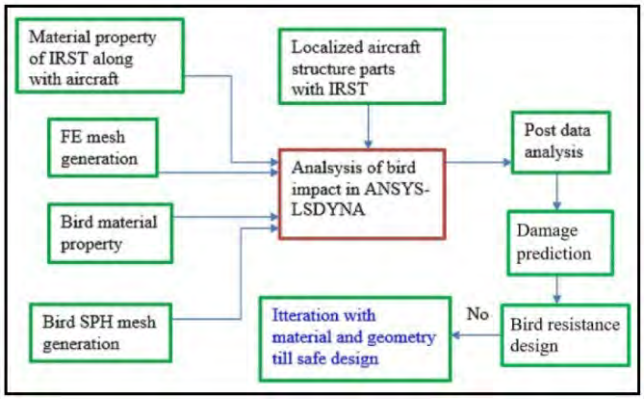


Fig. 9. Flowchart for designing bird strike resistant structure

A. Iteration I : WS frame material change to titanium

Front WS flange material is changed to titanium alloy and analysis has been carried out. Analysis results indicate reduced damage to WS forward arch as compared to base design. Only flange edge undergoes local damage, with damage area ~70 mm x 5mm shown in Fig. 10.

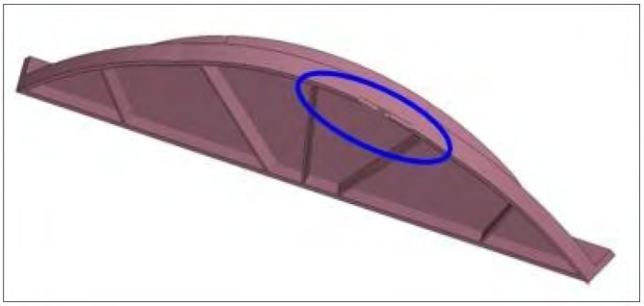


Fig. 10. WS Forward arch damage post bird impact

B. Iteration 2 : Base design with steel strip on flange and two triangular web stiffeners

As damage is seen to occur at edge of flange of WS forward arch, a 2 mm thick steel strip is incorporated as shown in Fig. 10 and sectional view is shown in Fig. 11. Additionally, two Aluminium triangular stiffeners of 5 mm thickness are provided on WS forward arch web both at front and rear (Fig. 10, 11(a) and 11(b)).

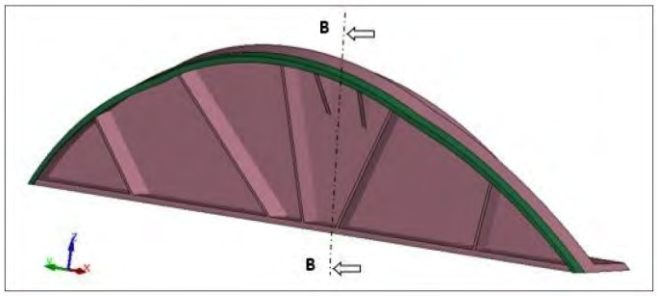


Fig. 10. Design modifications to WS forward arch

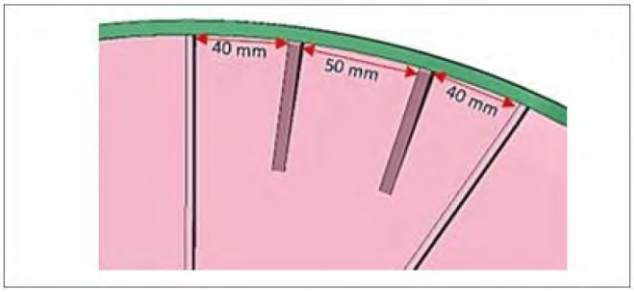


Fig. 11(a). Location of stiffener

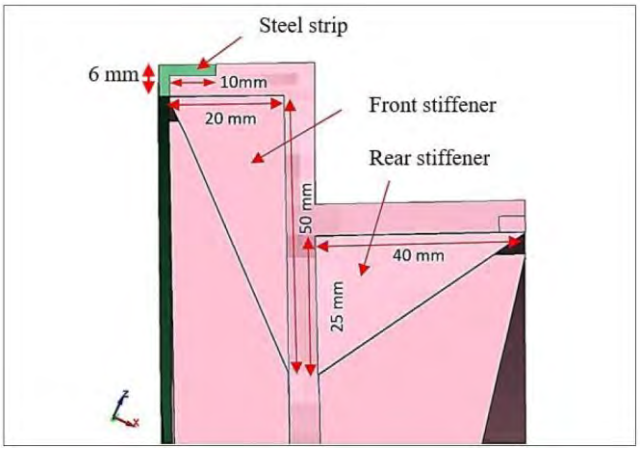


Fig. 11(b). Section B-B

Fig. 11. Stiffener location and cross section

Analysis results are shown in Fig. 12(a) and 12(b). It is seen that damage post bird hit is reduced as compared to base design. Steel strip deflects by 8 mm. Local damage is seen in following:

- Edge of flange - 80 mm x 10 mm
- Both triangular stiffeners - 20 mm x 5 mm
- Vertical web stiffener – 15 mm x 3 mm

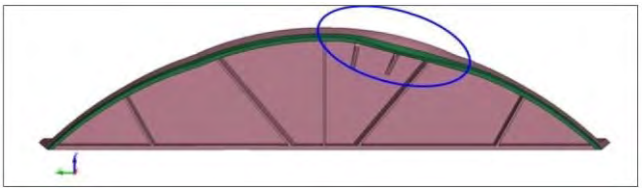


Fig. 12(a). WS Forward arch damage post bird impact

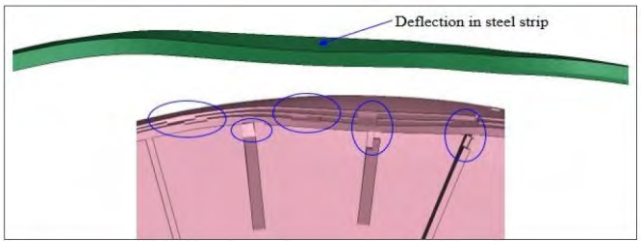


Fig. 12(b). Zoomed view of damage to WS forward arch components

Fig. 12. WS front frame damage

C. Iteration 3 : Base design with steel strip on flange and box Aluminium stiffeners

After studying analysis results from iteration II, triangular stiffener is changed to a box type stiffener. Following two modifications have been incorporated (Fig. 13 &14):

1) 2 mm thick steel strip at edge of flange, while maintaining total flange thickness of 6 mm.
2) Aluminium stiffeners of 4 mm thickness spanning region between the two central inclined web stiffeners (marked 1 & 2).

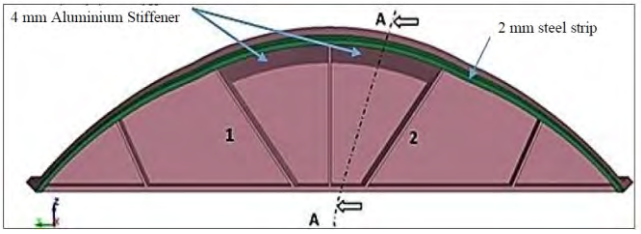


Fig. 13. Final modified design of WS forward arch

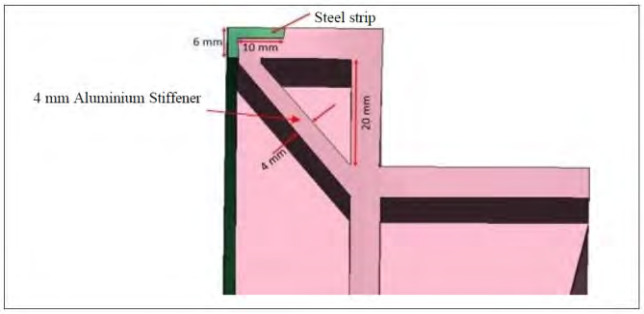


Fig. 14. Section A-A of WS forward arch

IX. ESTIMATION OF SAFE IMPACT SPEED

For both Cases I and II, analysis has been carried out iteratively by varying impact speed to arrive at maximum speed for which IRST system would not get damaged.

A. Max safe impact speed for 2.2 lb bird strike

Analysis results indicate that safe impact speed for 2.2 lb bird strike is ~ 540 kmph. Associated energy level is 11.25 kJ. Fig. 6 shows the structure post impact along with the stress and strain plots for IRST dome and kovar ring. Factor of safety considering max stress in IRST dome is ~1.1 and max strain in kovar ring is 5.

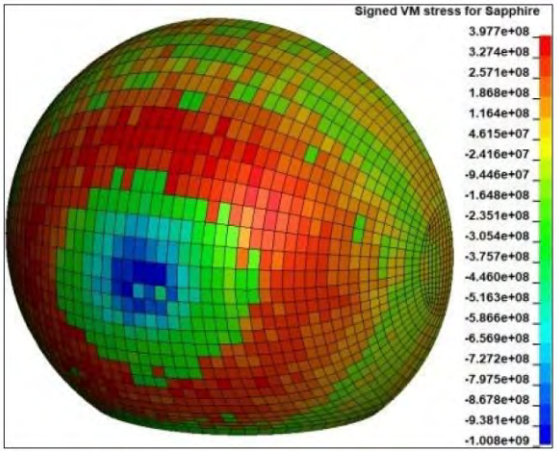


Fig. 15(a). Stress plot: IRST dome

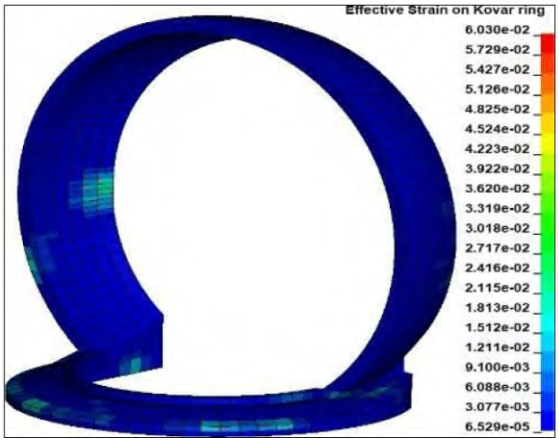


Fig. 15(b) Strain plot: Kovar ring

Fig. 15. Results for max safe impact speed for 2.2 lb bird hit

B. B. Max safe speed for 4 lb bird impact

Analysis results indicate that safe impact speed for 4 lb bird strike is ~ 450 kmph. Associated energy level is 14 kJ. Fig. 16 shows the structure post impact along with stress and strain plots for IRST dome and kovar ring respectively. Factor of safety considering max stress in IRST dome is 1.07 and max strain in kovar ring is 3.

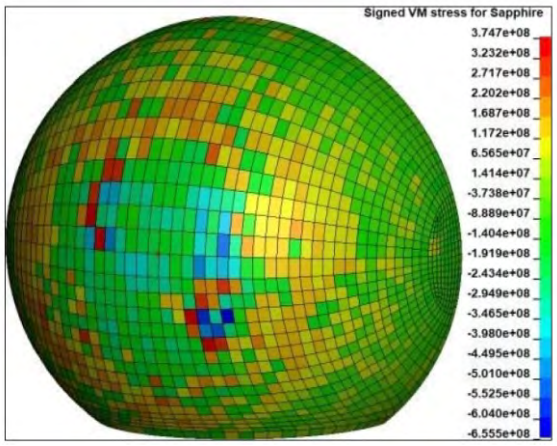


Fig. 16(a) Stress plot: IRST dome

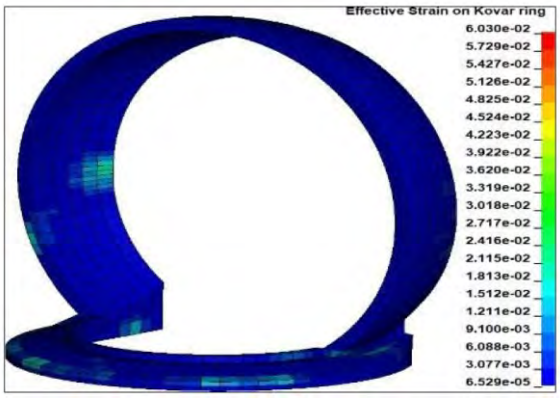


Fig. 16(b). Strain plot: Kovar ring

Figure 16. Results for max safe impact speed for 4 lb bird hit

X. CONCLUSIONS

1. The present study was carried out to evaluate bird strike resistance of IRST system and secondary impact on adjacent windshield structure. Two different impact loadings, 2.2 lb bird and 4 lb bird at speed of 850 kmph have been analysed.
2. Analysis results indicate that IRST system would not withstand the impact for both bird intensity cases. However, for 2.2 lb bird strike, structural damage to adjacent airframe is local and minor. The airframe would be able to land back safely post bird hit.
3. For 4 lb bird strike windshield forward arch is ruptured which may lead to cockpit depressurization. Design modifications have been proposed on WS forward arch with an associated marginal weight penalty of ~0.2 Kg. The revised design ensures airframe would be able to land back safely post bird hit.
4. Maximum impact speed at which the IRST system would be safe has been computed to be 540 kmph and 450 kmph for the 2.2 lb and 4lb bird hit cases respectively.

ACKNOWLEDGMENT

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Graph based Smart Neural Recommendation Mechanism (SNeRM) for system modelling

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Abstract - Creating a representation of real systems to evaluate its behavior can become very complex once multiple sub-systems are created that interact with one another. This can become especially challenging for inexperienced users who are trying to test out different concepts or validate with existing 3D real time systems. These challenges are mainly faced due to uncertainty on how to model or represent certain sub-systems, interconnecting different concepts and validation of results obtained from simulations.

This is where Smart Neural Recommendation Mechanism (SNeRM) with in-domain knowledge can aid users while designing these systems. These recommendation systems can be embedded with knowledge by training it on models created in the past by experts and build an understanding of the context with which the models were developed. These trained systems can assist other users with further development by providing recommen-dations based on the current intent of the user in an implicit manner.

In our current work, we have investigated the ability of contextually rich structured graphs to understand the different components within each circuit or system as well as the functional relationship between the components. These graphs are then broken down into smaller subgraphs to easily match with the circuit the user intends to create through a technique called Component Neuro Sub-Graph Matching

Keywords - Graph Neural Network, Knowledge Graph, Recommendation Engine, System Modelling

I. INTRODUCTION

System modelling requires expertise to understand systems and sub-systems and requires the skills to design using fundamental building blocks. For this, a theoretical as well as practical knowledge of the system is essential. In the aerospace industry, New Product Ingestion (NPI) for components such as aircraft engines requires multiple phases of development like Conceptual Design (CD), Preliminary Design (PD) and Detailed Design (DD). Architectures of the various subsystems such as cooling, combustion, mechanical components, and control systems are evolved and finalized in the initial phases of the development. Careful system design is essential to prevent the squandering of predevelopment resources and time and to guarantee safety during system testing. Hence, for aircraft engine related NPI development typically takes around 4-5 months for architecture to pass conceptual design

reviews. A significant amount of time is spent in adhering to design practices (DP) and design guidelines while designing such critical components. Additional time is spent in exploring novel architectures for 1D design modelling. Therefore, there is a need for an intelligent mechanism that can assist design engineers during the system modelling phase which can validate the designs based on past domain knowledge. Such a system would need to have an extensive knowledge of functional relationship between components and sub-component along with the right knowledge on the overall objective considering the individual component characteristics.

Earlier researchers address the above problem of knowledge modelling in conceptual design environment through building of knowledge component engine/databases [1] and employ bilinear function to capture the co-occurrence patterns of related items through Memory Augmented Graph Neural networks [2]

In this paper, we are proposing Smart Neural Recommendation Mechanism (SNeRM), a novel deep learning-based architecture inspired from [3] that can automatically recommend solutions in 1D system modelling to a design engineer in an implicit manner. The overall architecture utilizes contextually rich graphs that are created from domain specific models and capture the functionality of different components, their inter-connection, and the overall modelling intent. Using the Component Neuro Sub-graph matching, we dissect the 1D connected modules into sub-modules (sub graph) in an automated k-hop traversal and further, utilize the contrastively learnt graph embeddings to recommend the most probable network/modelling component.

The overall objective of this study is to show the overall effectiveness of graph-based recommendations system to assist users during the system modelling process of component designs.

II. ANALYSIS

A. Graph database generation for recommendations

The recommendation engine shown in this study is a type of content-based recommendation system where a similarity function between query and database 1D models is used to recommend more feasible next steps. In real time engineering systems (e.g : Cooling Systems in Aero Engines Gas Turbines, PCB design of electrical component, Refrigeration in air condition system), during the conceptual design phase, system modelling typically involves building/connecting multiple sub components (like valves, bearing, couplers) through 1D network modelling tools (e.g: AMESim [4] , Dymola [5]). An example of 1D modelling networks diagram (Aircraft Refrigeration System) is shown in Fig. 1 where for a given components like compressor, heat exchanger, there are specific domain rules embedded in the forms of the type of connection with the adjacent components, specific ports to be connected etc. In the current recommendation system, SNeRM model learns this domain specific relationship.

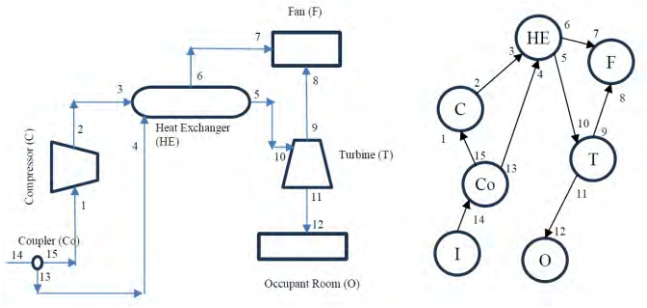

Figure 1: 1D modelling network diagram for Aircraft Refrigeration Systemwith Graph representation

between different components and make adaptive recommendations of the possible next steps understanding the current user state during modelling. To achieve the above objective, the conversion of the 1D models into domain graphs where each graph represents a particular design module is adopted. Particularly, the database containing multiple AMESim files corresponding to 1D designs of sub-systems across varied domains (Automobile, Aerospace, Electrical) are taken into consideration. The 1D design files graph

database involves the translation of Python design macro scripts to structured graphs with the components/subcomponents representing the design nodes and the connections between them representing the predicates. The type of components, their input/output ports and descriptions are embedded as features of the nodes (component embedding vocabulary) which will be detailed in Section B.

B. Recommendation Methodology

In order to build a component embedding vocabulary, each of the unique components that were used to create the different circuits are assigned a particular index number as well as the number of ports for each component were identified. To make the embedding more contextually rich, the component descriptions are obtained by providing a suitable prompt to a Large Language Model. To convert the description into a vector embedding, a sentence transformer model was used. Since the description of the components were not too large, a reduction in the description embedding size was performed to reduce the features needed to be learnt by the order embedding model. Finally, the 3 different features sets are concatenated to form a component embedding layer.

Using the features extracted from each AMESim circuit, a contextually rich graph of the circuit was created by interconnecting the relevant nodes with features from the component embedding vocabulary. These graphs were then used to train the Order embedding model (detailed in section 2.3) which creates an embedding to classify if a particular query graph is a subgraph of the target graph.

Overall methodology followed to create the Smart Neural Recommendation Mechanism (SNeRM) has been shown in Fig. 2. During the system modelling process, the SNeRM obtains the components added by the user in the design space which it treats as the Query Graph. Using the components present, additional feasible graphs are created which take into account a number of factors and are treated as Target graphs. These query and target graphs are then converted into the order embedding space to identify which of the feasible graphs are the best suited target graph based on the embedding value.

This is then used to suggest the potential recommendations to the user.

C. Order Embedding Model

In this paper, we use the concept of order embedding based on (3), a novel technique that plays a pivotal role in searching for isomorphic subgraphs over target graphs, since the subgraph relationships induce a partial ordering over subgraphs introducing geometrical constraints over graphical structures, allowing us to use order embedding.

Order embedding is a special type of monotonic functions which transforms features into continuous vector representation preserving both inherent ordering and order reflection, enabling model to understand user intent and recommend accordingly.

Order embedding captures subgraph relationship, consider graphs G1 and G2, G1is subgraph of G2 then nodes of G1 and G2 must satisfy the constraint, embedding for node in query graph must be less than equal corresponding node embedding of target graph. This property allows the node embedding of node in G1 will be below right of the embedding of corresponding node in G2. Once order Embeddings are calculated, max-margin loss function is used to capture the subgraph relations, enhancing the recommendations.

D. Subgraph Prediction function

For any given node embedding in the target graph (z_u) where $u \in GT$ and node embedding in the query graph (z_q) where $q \in GQ$, the subgraph prediction function decides whether if u has k-hop neighbourhood that is a isomorphic subgraph of q's k-hop neighbourhood. The prediction is made only based on the embedding, if q is a subgraph of u, then the order embedding of z_q must be to the lower-left to the embedding of z_u.

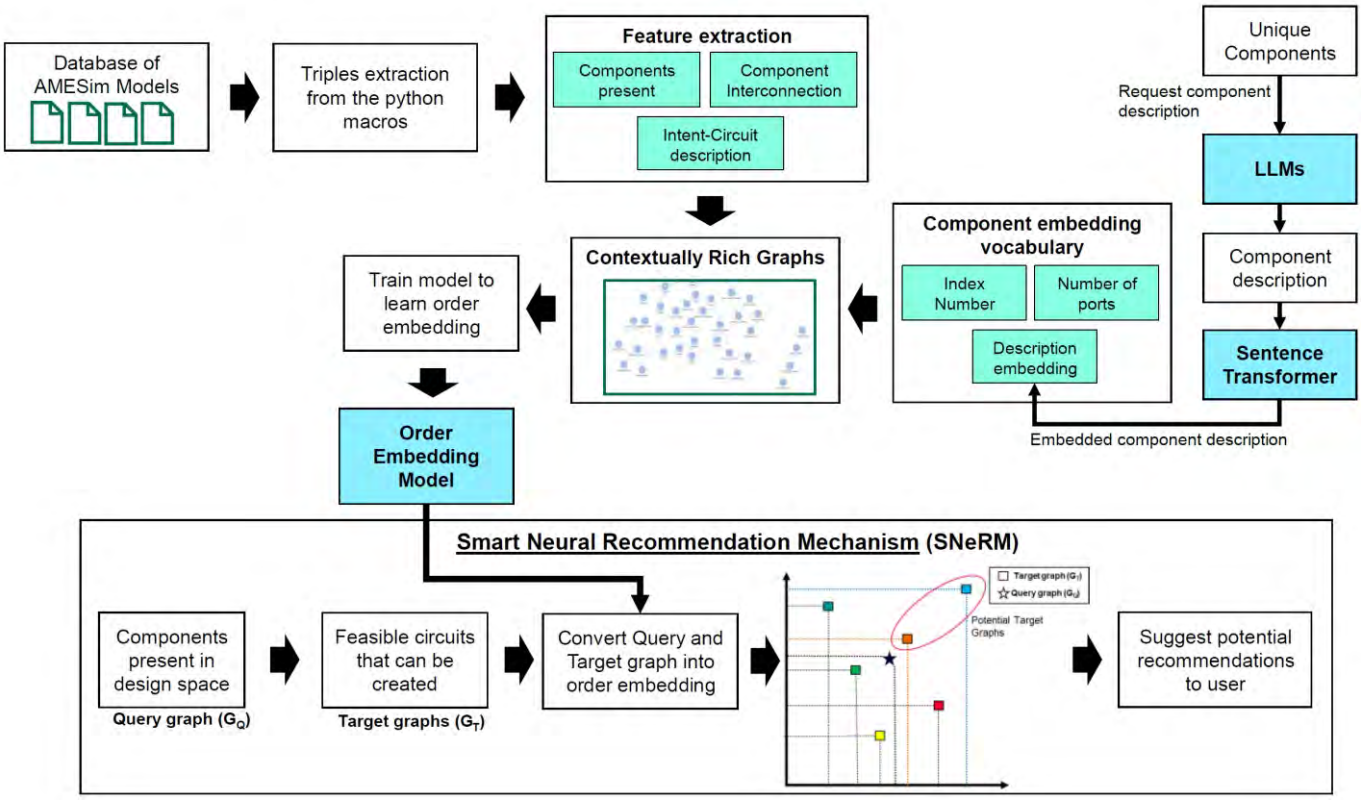

Figure2:Methodology

$$z_q[i] \leq z_u[i] \; \forall_{i=1}^{D} \quad if \; G_q \subseteq G_u \qquad (1)$$

where D is the embedding dimension. Hence, we train the GNN (Graphical Neural Network) that learns the order embeddings based on the max margin loss:

$$\mathcal{L}(z_q, z_u) = \sum_{(z_q,z_u)\in P} E(z_q, z_u) + \sum_{(z_q,z_u)\in N} max\{0, \alpha - E(z_q, z_u)\} \quad (2)$$

$$E(z_q, z_u) = ||\, max\{0, z_q - z_u\}||_2^2 \qquad (3)$$

Here P denotes the set of positive examples in minibatch where the neighborhood of q is a subgraph of neighborhood of u, and N denotes the set of negative examples.

E. Provide recommendation to user

Based on the subgraph prediction function mentioned in the previous subsection, the graph of the components present within the 1D modelling design space is considered as the query graph with an embedding z_q. Multiple feasible components can be added to the current design space to produce multiple target graphs with each graph having a particular embedding z_u. Any of the multiple graphs produced can be considered as a valid recommendation if the query graph node embedding lie in the lower-left of the target graph node embedding as shown in Fig. 3.

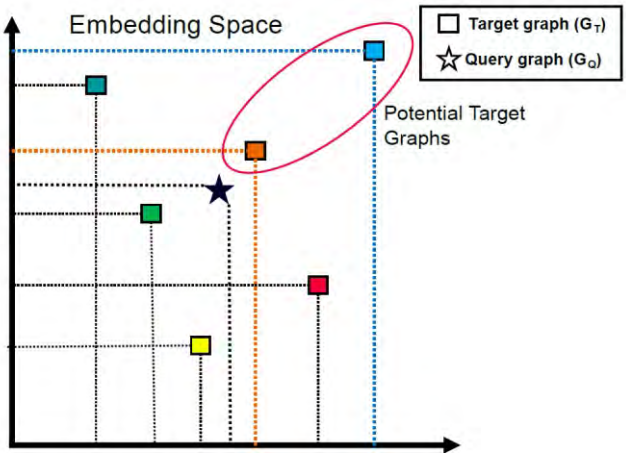

Figure 3: Recommendation based on order embeddings.

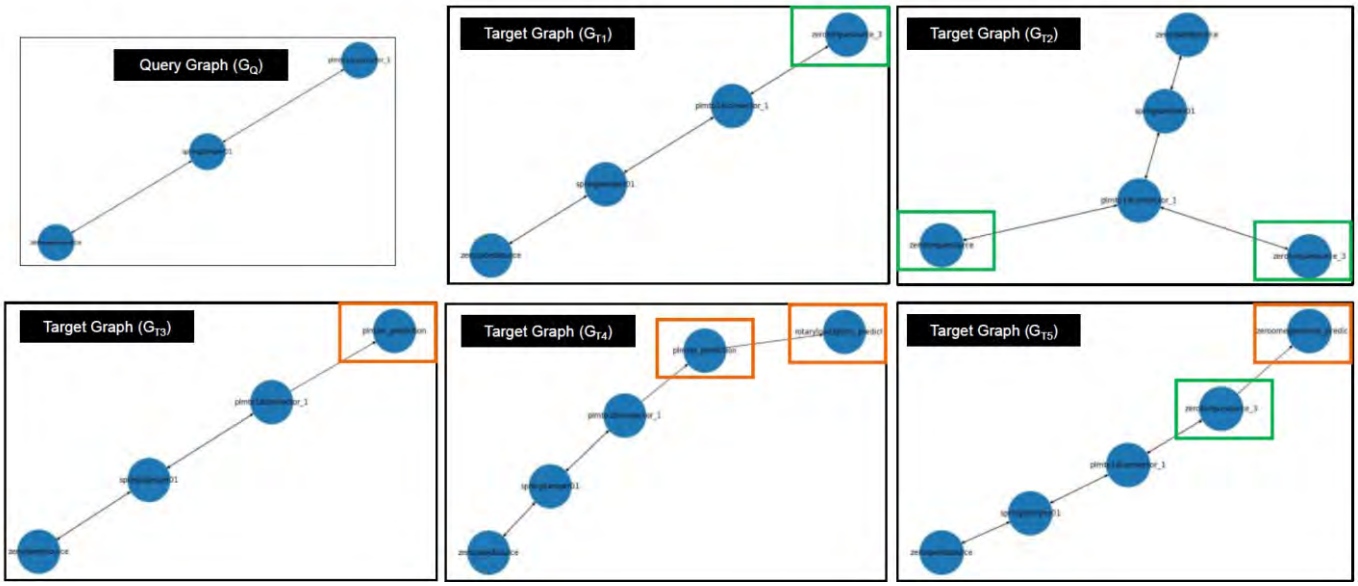

Figure 4: Query graph (G_Q) and Target graphs (G_{T1}, G_{T2}, G_{T3}, G_{T4}, G_{T5})

III. RESULTS AND DISCUSSION

A. Recommendation mechanism

The graph-based recommendation neural network is trained on 1D modelling dataset consisting of around 40 AMESim circuits. The features such as components present, their interconnection as well as the circuit description were extracted from the python scripts associated with these circuits. These circuit features were then used to construct graphs with inter-connected nodes consisting of nodes with embeddings obtained from the component embedding vocabulary.

The embedding vocabulary consists of 104 unique components which were assigned unique index values as well as number of ports for each of the components were assigned based on values observed in the scripts. The description embedding was created by firstly obtaining the description of each components through use of prompts on ChatGPT using LangChain to automate the process. The description were then passed through the all-MiniLM-L6-v2 sentence transformer since is it faster than other available models while still offering good quality. The model embeds text to a 384-dimensional dense vector space however, further dimension reduction was performed to 32-dimensional vector space by using PCA (Principal Component Analysis) Technique. This gave an overall node-level embedding size of 36 consisting of index number, number of ports and the description embedding.

The graphs constructed were then used to train the Order Embedding model. Learning rate was set to 10^{-5} and embedding size of 64 was used.

B. Recommendation Validation

To test the accuracy of the recommendations to the users, 29 different scenarios were considered. From the already existing circuits, a three-component circuit was obtained and assumed to be the initial components present in the design space. This circuit in the graphical form is the query graph (G_Q) and 4 corresponding target graphs were created. Target graph G_{T1} and G_{T2} were the actual circuit graph with additional 1 and 2 correct nodes respectively. The target graphs G_{T3} and G_{T4} were incorrect circuit graphs with 1 and 2 randomly chosen incorrect nodes respectively. The target graph G_{T5} contains one correct node and one incorrect node. An example for the graphs that were generated are shown in Fig. 4.

Each node in the query was compared with the order embedding for nodes the target graphs based on the subgraph prediction function (3). This provides a matrix with rows as query nodes and columns as target graph nodes also referred to as

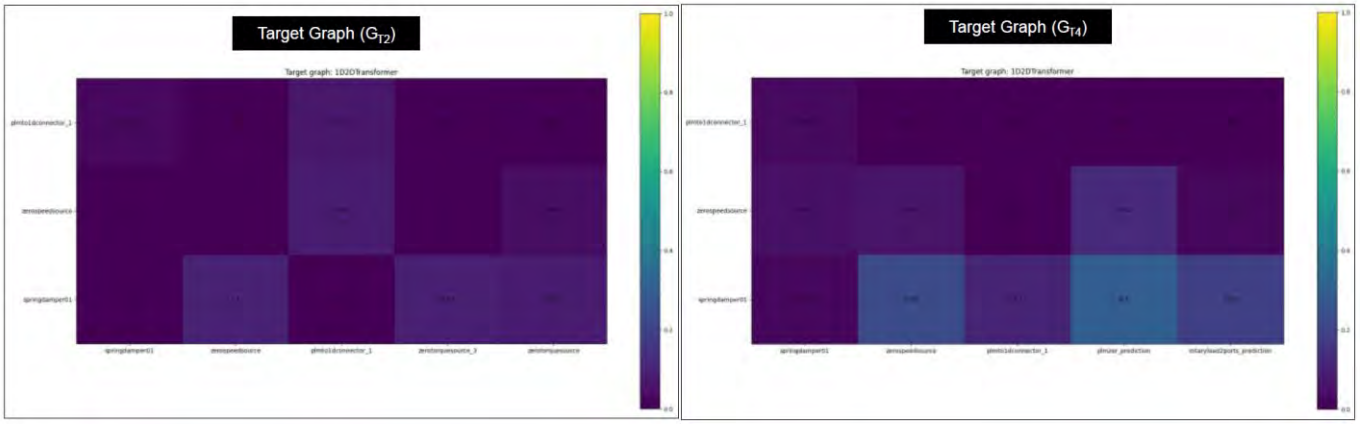

Figure 5: Alignment matrix for Two-level node prediction Target Graph T_{G2} and T_{g2}

the alignment matrix. The alignment matrix for the target graphs G_{T2} and G_{T4} are shown in Fig. 5. Matrix elements with value of zero means that for that particular anchor node combination, the query is a subgraph of the target graph based on the values learnt by the GNN. Whereas a non-zero value indicates some misalignment in the order embedding space. To identify if the order embedding was able to correctly differentiate between the correct and incorrect target graph predictions, the mode of the alignment matrix was used as it refers to the most frequent value.

C. Results

The mode of the alignment matrix for each query and corresponding target graphs along with the difference in the mode values for only the two-level node prediction target graphs G_{T2} and G_{T4} in shown in Fig. 6. The order embedding model was correctly able to differentiate between the correct and incorrect prediction with an accuracy of 79.31% for the two-level node prediction whereas the accuracy for one-level node prediction was around 55%. In terms of Recommendation Metric, Mean Reciprocal Rank (MRR), the current model delivers >82.1%. This shows that the model can provide the user with a correct recommendation of the potential next components that he would like to add to the current circuit being designed without any user intervention.

	One Level Node Prediction		Two Level Node Prediction			Difference	Rank of TG2
	TG1	TG3	TG2	TG4	TG5	Δ(TG4,TG2)	
QG1	0.001	0.015	0.0000	0.0214	0.0077	0.021	1
QG2	0.000	0.037	0.0000	0.0010	0.0016	0.001	1
QG3	0.001	0.002	0.0000	0.0054	0.0000	0.005	1
QG4	0.000	0.000	0.0000	0.0168	0.0134	0.017	1
QG5	0.000	0.004	0.0022	0.0015	0.0013	-0.001	3
QG6	0.041	0.010	0.0000	0.0010	0.0019	0.001	1
QG7	0.019	0.006	0.0001	0.0006	0.0050	0.001	1
QG8	0.003	0.002	0.0009	0.0023	0.0020	0.001	1
QG9	0.008	0.166	0.0307	0.1710	0.0242	0.140	2
QG10	0.000	0.007	0.0000	0.0006	0.0000	0.001	1
QG11	0.055	0.028	0.0943	0.0904	0.0142	-0.004	3
QG12	0.002	0.001	0.0001	0.0054	0.0057	0.005	1
QG13	0.132	0.069	0.1702	0.1482	0.0800	-0.022	3
QG14	0.002	0.000	0.0062	0.0249	0.0036	0.019	2
QG15	0.040	0.173	0.0154	0.2008	0.0569	0.185	1
QG16	0.000	0.000	0.0000	0.0274	0.0015	0.027	1
QG17	0.000	0.001	0.0000	0.0022	0.0007	0.002	1
QG18	0.016	0.018	0.0671	0.0424	0.2094	-0.025	2
QG19	0.003	0.012	0.0001	0.0010	0.0002	0.001	1
QG20	0.000	0.001	0.0000	0.0021	0.0000	0.002	1
QG21	0.011	0.008	0.0000	0.0011	0.0000	0.001	1
QG22	0.000	0.001	0.0000	0.0064	0.0016	0.006	1
QG23	0.000	0.012	0.0000	0.0232	0.0049	0.023	1
QG24	0.002	0.000	0.0001	0.0006	0.0000	0.000	2
QG25	0.002	0.000	0.0000	0.0017	0.0010	0.002	1
QG26	0.001	0.018	0.0000	0.0092	0.0000	0.009	1
QG27	0.000	0.001	0.0077	0.0012	0.0181	-0.006	2
QG28	0.231	0.025	0.0771	0.0595	0.0036	-0.018	3
QG29	0.028	0.015	0.0010	0.0017	0.0097	0.001	1

Figure 6: Mode of the aligment matrix for target graphs with query graphs

IV. CONCLUSION

In this paper, we have demonstrated the feasibility of design assistance/recommendation engine using sub-graph matching techniques on top of existing 1D design models. Further by testing on real-time cases, we have been able to accomplish higher accuracy/MRR scores. Some unique novel outcomes from this effort are:

- Knowledge fusion of component description and their functional relationships which can be utilized for objective based learning.
- Deliver on an inductive graph intelligence architecture which can used in domain specific transfer learning.

- Show the value of recommendations (that are mostly prevalent in information retrieval world) for real time mechanical/electrical system design engineering.

With these technique, it should help in reducing manual efforts and leveraging the database knowledge for 1D System modelling.

V. ACKNOWLEDGEMENT

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Numerical Simulation of Test Fixture And Experimental Verification by Full Scale Slosh & Vibration Test of Aircraft External Fuel Tank

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Abstract - External fuel tanks (drop tanks) are carried on modern combat aircraft to enhance range and to facilitate completion of mission objectives. In the event of an emergency or to ensure quick pilot getaway from enemy territory, drop tanks are designed to be jettisonable. One of the important qualification tests for drop tanks is the test under simultaneous slosh and vibration loadings.

This paper summarizes the free vibration analysis study of slosh and vibration test fixture for a 1200 lt external fuel drop tank used in a generic combat aircraft. The main objective of this analysis was to ensure a robust and dynamically stable design of test fixture capable of simulating slosh and vibration conditions that occur during flight and ground operational conditions. Experimental tests were carried out using the designed fixture, with the drop tank subjected to controlled slosh and vibration excitation as per MIL-T-7378A. Various sensors such as accelerometers, pressure sensors and strain gauges were used to capture the drop tank and test fixture responses during test. The acquired experimental modal data was then compared and correlated with analytical simulation results and a good match was seen.

Keywords - Aircraft, Drop tank, Slosh, Test fixture, Vibration.

I. INTRODUCTION

Drop tanks are exposed to different dynamic environments during ground and flight operations of a combat aircraft. This may be due to rigid body motion, aircraft manoeuvres, flow induced oscillations and internally generated vibrations etc. which are transmitted via attachment points of the drop tank in form of accelerations. Reference [1] specifies slosh & vibration loading levels for qualification of jettisonable external fuel tank for fighter aircraft. This slosh & vibration test comprises vibration at a frequency of 2000 ± 60 cycles / minute (33.33 Hz) with minimum double amplitude of 0.02 inches and slosh of ±15° about the pivot point at a frequency of 10 cycles / minute for a duration of 25 hours.

A generic combat aircraft which carries drop tanks at wing inboard, midboard and under fuselage stations to enhance the range of the aircraft has been taken for a case study. Adhering to slosh & vibration loading specifications outlined in [1], a test was planned to assess the structural integrity, reliability and performance of the external drop tank of the generic combat aircraft under various conditions which it will encounter during service life. The objectives of the test were to demonstrate ability of drop tank to withstand slosh and vibration (there should be no leakage or structural damage to the drop tank after the test) and to enhance drop tank life to full aircraft life.

Towards this, a test fixture was designed and fabrication and conduct of tests was taken up at CSIR-SERC, Chennai. A free vibration analysis was carried out on the test fixture using MSC NASTRAN solver. The main objective of the analysis was to determine the natural frequencies for three different cases, namely test fixture, test fixture with empty and with 2/3rd water filled drop tank. This facilitates assessment of system natural frequen-

cies so as to ensure their separation from MIL specified input excitation frequency of ~33.33 Hz.

A test-analysis correlation of the normal modes of the test fixture measured during test and simulated analytically has also been presented.

Reference [2] presents the problems and lists precautions to be taken while conducting slosh and vibration test for a metallic drop tank. Details of test system developed and requirements of main components of the fuel tank slosh & vibration test equipment is presented in [3]. The author has discussed finite element modelling of machinery vibration isolation systems to minimize vibration response transmissibility [4].

II. MODELLING AND ANALYSIS

The three dimensional CAD model of slosh and vibration test fixture was idealized using CATIA and is shown in Fig. 1. The structure comprises top and bottom frame which houses the drop tank. A mechanical shaker is employed for providing vibration excitation and a single actuator induces the sloshing motion. Vibration isolators are utilised to isolate the input vibration from the actuator.

A finite element (F.E.) model of the test fixture was created in HYPERMESH and MSC PATRAN (Fig. 2). The FE idealizations used for analysis of slosh and vibration test fixture are as follows:

- All components of test fixture except vibration isolators are idealized using four nodes CTETRA elements.
- Vibration isolators are modelled using CELAS1 elements
- Pylon and drop tank are modelled using CBAR. CONM2 elements are used to idealize the mass properties.
- Pin is idealized using CBAR and RBE3 elements for the lug connections.
- Mass properties of mechanical shaker are idealised using RBE3 and CONM2 elements.

During tests, test fixture was mounted on a pedestal which was fixed rigidly to the ground. Boundary conditions used in the analysis, to simulate test conditions are as follows (Fig. 2):

Location 1: Tx = Ty =Tz = 0, Ry = Rz = 0
Locations 2 & 3: Tx = Ty =Tz = 0, Rx= Ry = Rz = 0 (boundary conditions at location 2 are for neutral or 0o position only)

The drop tank is made of Glass Fibre Reinforced Plastic (GFRP) composite. Mass, centre of gravity and moment of inertia of fixture with empty and 2/3rd water filled drop tank for three cases namely, drop tank in neutral or 00 position, 150 pitch up & 150 pitch down positions were determined. F.E. model mass of ~3025 kg is considered in the analysis with 2/3rd water filled drop tank.

The test fixture was fabricated using mild steel hollow sections and plates. Three aluminium alloy beams with bolts to facilitate pylon connection as in aircraft and referred to here as Main beams were integrated with the test fixture. Drop tank is mounted on the pylon. Material properties used for the test fixture analysis are shown in Table 1.

TABLE 1.
MATERIAL PROPERTIES OF THE TEST FIXTURE

Description	Material	E(MPa)	ν	Density (kg/mm3)(x10-6)
Mains Beams	Al_alloy	70000	0.30	2.71
Fixture frame	Mild steel	210000	0.30	7.86

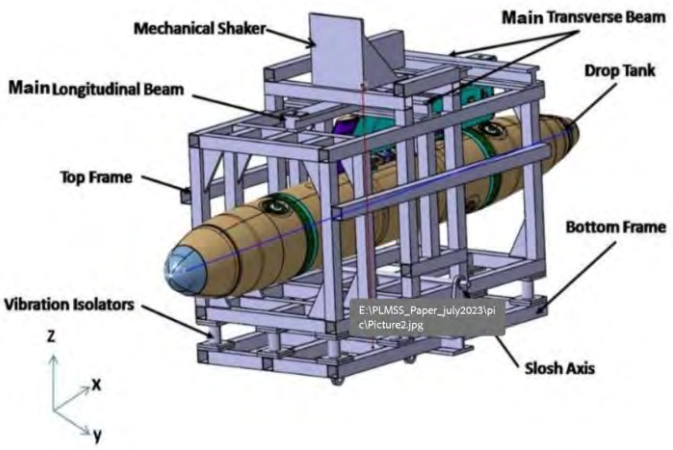

Fig. 1. CAD model of test fixture with drop tank

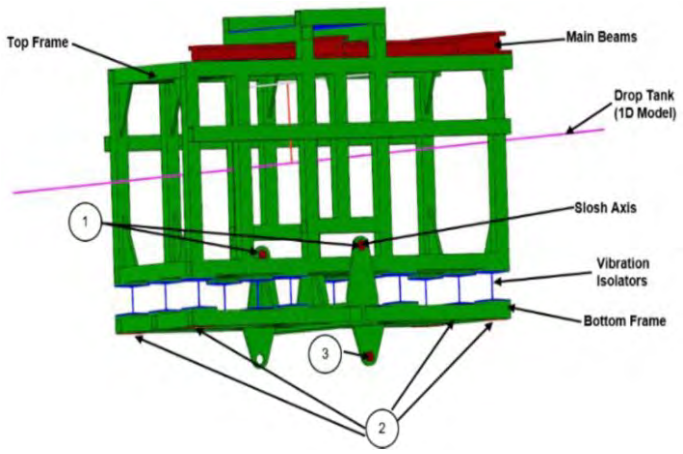

Fig. 2. F.E. model of test fixture with drop tank

A. Free Vibration Analysis

Normal mode analysis was carried out on the F.E. model of test fixture without drop tank, test fixture with empty and with 2/3rd water filled drop tank 00 position. For the third case, additionally, 150 pitch up and 150 pitch down positions were also analysed.

Since the input excitation frequency is ~33.33 Hz, first few normal modes with frequencies within 100 Hz have been computed from analysis. Test analysis correlation has been carried out with available test data and comparisons are shown.

B. Resonance Search Test

Before the start of slosh and vibration test, impact hammer test and resonance search test were carried out to identify the frequencies and mode shapes for the test fixture for different cases (i) Case I : without drop tank, (ii) Case II : with empty drop tank and (iii) Case III : with 2/3rd water filled drop tank. Resonance search test was carried out on the test fixture, using sine sweep excitation from 1 to 300 Hz.

III. RESULTS AND DISCUSSION

The acquired experimental data for free vibration of test fixture was compared and correlated with the predicted analytical simulation results.

A. Case I: Test Fixture Without Drop Tank

Analytically predicted natural frequencies (within 100 Hz) of test fixture without drop tank for 00 position are listed in Table 2. Comparison with test results shows a good match, with differences within 10%. Associated mode shapes for test fixture without drop tank are shown in Fig. 3 to Fig. 5. The first low frequency top frame plunging mode can be attributed to the vibration isolation springs.

TABLE 2. NATURAL FREQUENCIES OF TEST FIXTURE WITHOUT DROP TANK

SN	Mode Description	Frequency (Hz) (analysis)	Frequency (Hz) (Test)	Difference %
1	Top frame plunging	7.3	7.1	3.0
2	Top frame twisting	77.4	69.7	9.9
3	Top frame pitching + twisting	84.6	83.7	1.0

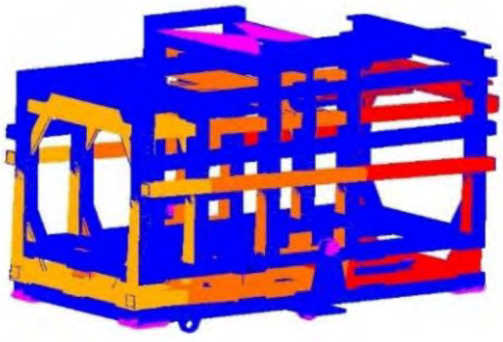

Fig. 3. Top frame plunging mode (7.3 Hz)

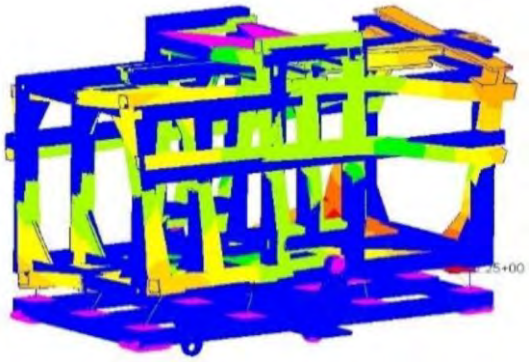

Fig. 4. Top frame twisting mode (77.4 Hz)

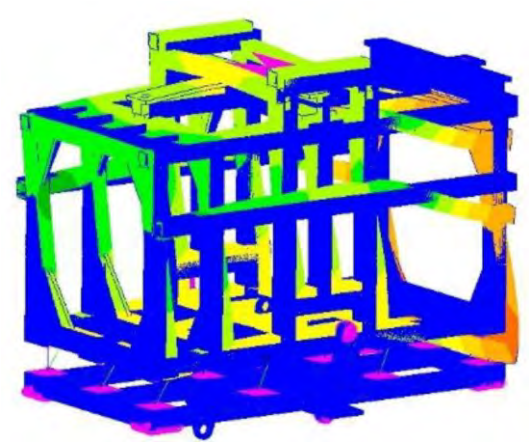

Fig. 5. Top frame pitching + twisting mode at 84.6 Hz

B. Case II: Test Fixture With Empty Drop Tank

The first three natural frequencies of test fixture with empty drop tank for 00 position are listed in Table 3 and compared with test results. The first low frequency top frame plunging mode can be attributed to the vibration isolation springs. It is seen that the analysis predictions show a very good match with test data (differences are within 2%). Associated mode shapes are shown in Fig. 6 to Fig. 8.

TABLE 3. NATURAL FREQUENCIES OF TEST FIXTURE WITH EMPTY DROP TANK

SN	Mode Description	Frequency (Hz) (analysis)	Frequency (Hz) (Test)	Difference %
1	Top frame + DP plunging	6.9	6.7	1.6
2	DT vertical bending I + Top frame pitching & bending	66.8	66.2	0.9
3	DT vertical bending II + Top frame pitching & bending	97.4	98.1	-0.7

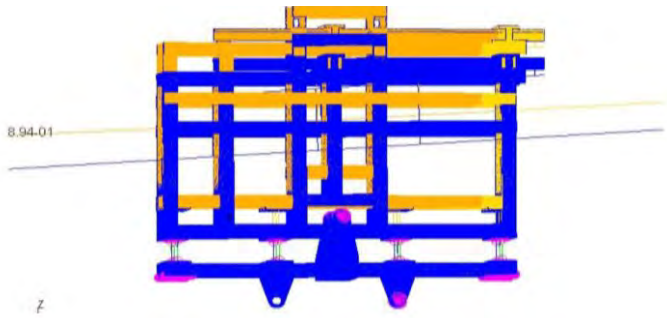

Fig. 6. Top frame + DT plunging mode at 6.9 Hz

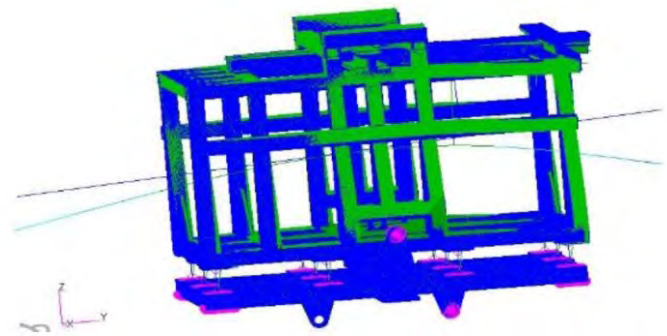

Fig. 7. DT vertical bending+Top frame pitch & bending mode at 66.8 Hz

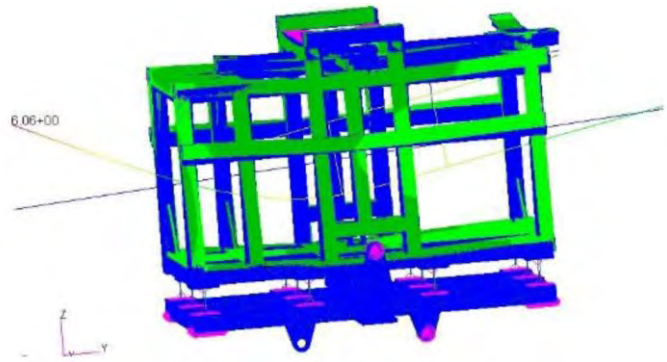

Fig. 8. DT vertical bending II +Top frame vertical bending mode at 97.4 Hz

C. Case III: Test Fixture With 2/3rd Water Filled Drop Tank

Case III considers the drop tank configuration to be used for slosh & vibration testing. Therefore two additional analysis have been carried out for extreme sloshing positions.

The first three natural frequencies of the test fixture with 2/3rd water filled drop tank for neutral and two extreme slosh rocking positions (00 position, 150 Up and 150 Down) are tabulated in

Table 4 and associated mode shapes are shown in Fig. 9 to Fig. 11.

The first low frequency top frame plunging mode can be attributed to the vibration isolation springs. The next two modes are related to drop tank first and second vertical bending coupled with top frame pitching.

Analytical frequencies for 00 position case are compared with test results and differences are seen to be within 5%.

Further, analysis results indicate that for ±150 i.e., slosh rocking extreme positions, natural frequency variations are seen to be within 7% w.r.t. frequencies at 00 position.

TABLE 3. NATURAL FREQUENCIES OF TEST FIXTURE WITH EMPTY DROP TANK

SN	Mode Description	Frequency (Hz)						
		0°Position			15° Up		15° Down	
		Test (A)	Analysis (B)	Diff., % (B vs A)	Analysis ©	Diff., % (C vs B)	Analysis (D)	Diff., % (D vs B)
1	Top frame +DP plunging	5.5	5.5	0.0	5.3	-3.6	5.4	-1.7
2	DT vertical bending II + Top frame pitching & bending	27.3	28.6	4.5	29.8	4.1	29.1	1.8
2	DT vertical bending II + Top frame pitching & bending	46.7	44.6	-4.7	46.4	3.9	41.9	-6.4

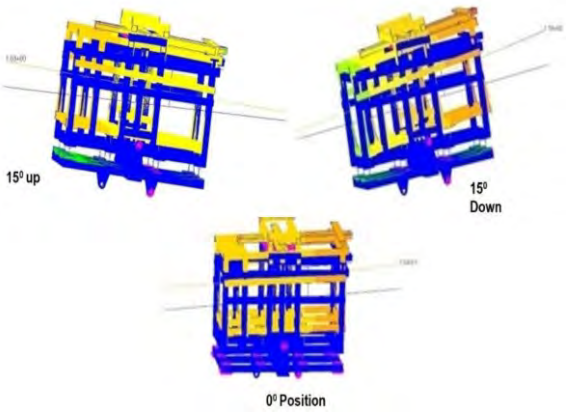

Fig. 9. Top frame + DT plunging mode at 5.3 Hz, 5.4 Hz and 5.5 Hz (150 Up, 150 Down and 00 Position)

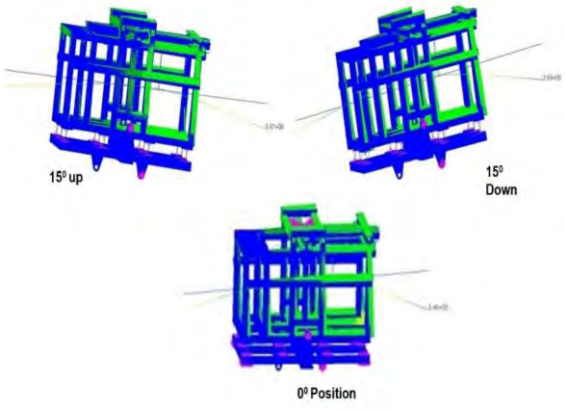

Fig. 10. DT vertical bending I+ Top frame pitching mode at 29.8 Hz, 29.1 Hz and 28.6 Hz (150 Up, 150 Down and 00 Position)

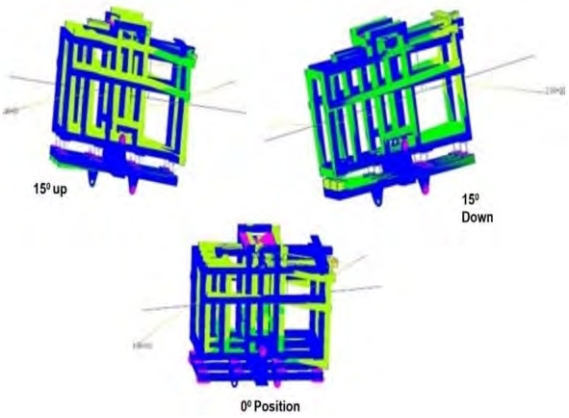

Fig. 11. DT vertical bending II + Top frame pitching mode:46.4 Hz, 41.9 Hz and 44.6 Hz (150 Up, 150 Down and 00 Position)

IV. CONCLUSION

Free vibration analysis was carried out on the simplified FE model of test fixture for different cases (i) without drop tank, (ii) with empty drop tank and (iii) with 2/3rd water filled drop tank. The last case is the MIL specified test case and was further analysed for two slosh rocking extreme positions (150 Up, 150 Down).

Test analysis correlation of natural frequencies within 100 Hz has been carried out and a good match is seen. The differences between test data and analysis predictions for natural frequencies of test fixture are within the acceptable percentage limit, 10% for the three cases analysed.

Drop tank slosh and vibration tests could be carried out successfully with the designed test fixture paving the way for life enhancement of drop tanks to full aircraft life.

ACKNOWLEDGMENT

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Configuration and Customization of a PLM Software for the Computer-Aided Engineering (CAE) Data Management

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Abstract - In today's world, digital simulations are essential in the product development process, starting from the product's conception to its validation. The three main stages of Computer-Aided Engineering (CAE) simulation processes are pre-processing, solving, and post-processing. It's important to manage the design, simulation data, and process information effectively to track the engineering part all the way from its inception/ design stage through simulation studies to the approval phase. In this regard, an integrated design and simulation lifecycle management system is implemented on the 'Teamcenter' platform at Structural Technologies Division, CSIR-NAL, in association with the system integrator. The implemented system ensures that all pertinent data and processes are securely managed. A unique concept is proposed and implemented through configuration as well as customization of the Teamcenter application, which helps to trace the engineering part from its design stage to the end of simulation studies, including the stage of geometric simplification considered for CAE studies. The details are presented in this paper.

Keywords - CAE, DSLM, PLM, Teamcenter, Customization

I. INTRODUCTION

It is truly remarkable to observe the evolution of the engineering processes and procedures used in the design and development of aircraft. We have progressed beyond the days of relying solely on 2D drawings and manual analyses. Thanks to the development of advanced 3D modeling, computing, and simulation methods, we are now able to experience aircraft design and development in immersive 3D visualization and virtual reality scenarios. During the early stages of product development, it's crucial for designers to choose the best possible design from a vast array of options. Computer-Aided Engineering (CAE) simulations are an excellent tool for achieving this, as they allow for accurate and effective assessments of the various designs before any actual construction takes place. Thus, simulations help in reducing product development time and cost. It's interesting to note that CAE tools are becoming increasingly common in the Aerospace and Automobile industries for simulation studies. Pertaining to the aircraft design and development programs, the best simulation processes (structural, kinematic, and layout optimization, etc.) being performed at the Structural Technologies Division, CSIR-NAL is considered for the simulation lifecycle management (SLM) system implementation [1].

II. COMPUTER-AIDED ENGINEERING (CAE) DATA MANAGEMENT

The implemented simulation lifecycle management system is capable of capturing the complete simulation scenarios along with their key parameters and associated files. CAE tools being used at the division, like Altair Hyperworks, MSC/Nastran, Patran, etc., and the in-house computational codes are considered for integration with the simulation lifecycle management system implemented on the Teamcenter platform. CAE simulation tools and in-house developed computational codes are integrated with the Teamcenter application through respective file datasets. The supported datasets for these simulation tools are predefined and are visible as part of the CAE items.

To enhance the computational performance, we simplify the complex product geometry based on its physical behaviour while ensuring that the results remain accurate and reliable. Thus, geometric simplification is indeed a crucial component of the pre-processing phase of simulation studies. It helps to streamline the simulation process and make it more efficient.

A distinctive naming system is proposed for simplified CAD geometric items and customized the Teamcenter application to implement it. The identification of each simplified CAD item will include a prefix of 'CAE' followed by the sixteen-digit number of its reference CAD model. Additionally, each item will have its own unique revision ID. A simplified CAD item revision form is defined with general attributes like Item description, reference details, versions of the CAD tools used, units of mass & length considered, material description and design criteria, etc.

Simulation models like finite element mesh will be prepared on the basis of simplified/idealized CAD geometry. A unique naming system is proposed for these CAE simulation files and implemented by customizing the Teamcenter application. CAE item name will carry the reference simplified CAD part number, including the revision id, simulation process tag for which the files are being used and simulation process-related attributes, etc. If the predefined attributes cannot meet the required specification, then the user can define the new process attribute. CAE tools are integrated with the Teamcenter through respective file datasets. All relevant file extensions are grouped under the respective CAE tool folders so that users can easily identify and work on the required files. CAE item revision form is defined with general attributes like Item description, user comments, reference details, versions of the CAE tools used, assumptions made, units for mass, length & force considered, finite element model-related details like mass & cg, idealizations made, material description & allowable, loads description, boundary conditions considered and design criteria, etc. In general, a simulation task may require few of the listed CAE tools and not all to complete the task. Hence, Teamcenter is customized to permit the users in downloading only the relevant CAE tool files to a local system. Thus, users can work offline on any of these downloaded files by using their native applications. For ease of traceability, it is proposed to replicate the simplified CAD assembly structure into finite element model construction, like defining Hypermesh components & assemblies in line with that of simplified CAD parts & assemblies. Thus, the implemented simulation lifecycle management system helps in tracing the part from its design stage to the end of simulation studies, including the stage of geometric simplification/ idealization. These simulation files that are worked offline will be imported back into the Teamcenter database.

Teamcenter application is customized so that the users can submit the analysis job on high-performance computing servers available on the local wide area network, check the status, and end the session after job completion. Users can select Solvers like Nastran, Abaqus, etc, and set the computing server parameters like the number of cores and the number of nodes. The queuing system is implemented so that the job will get executed automatically upon obtaining the software license and computing resources. Users can check the status of job execution. After the completion of the job, users can end the session, which will import all the relevant files into the Teamcenter database. Simulation results can be viewed/analyzed by using native post-processing tools. Teamcenter application is configured and customized to arrive at the stated simulation lifecycle management system.

Teamcenter is based on a client-server architecture. Both the client and server layers can be customized [2]. As stated, the proposed simulation lifecycle management system with distinct naming system for the simplified CAD and CAE items calls for configuration as well as customisation of the Teamcenter application. Customisation of the Teamcenter application is carried out using Java development tool. In general, the customisation includes the definition

of menus, sub-menus, customised user interfaces, programs to perform specific tasks, etc. The configuration and customisation carried out on Teamcenter application CAE tool is discussed here in details.

III. CUSTOMISATION AND CONFIGURATION OF TEAMCENTER APPLICATION FOR CAD DATA MANAGEMENT

The configuration & customization of the Teamcenter application for CAE data management started with configuring the CAE tools file types (different extensions) as datasets of the Teamcenter application. The different CAE tools file types are considered and the corresponding datasets are created in the Teamcenter BMIDE environment through configuration. Some of the file type extensions are common to some of the CAE tools considered for the configuration. This is addressed by giving the different names to each dataset representing common file types of the different CAE tools. Typical dataset configuration in Teamcenter BMIDE is shown in Fig. 1. Once datasets are configured, it is deployed to Teamcenter, and a configured main menu called 'CAE' appears. Under the main menu three sub-menus named 'Create Dataset',' Launch Session' and 'End Session' appear in the Teamcenter application as shown in Fig. 2. Whenever the user selects the sub-menu 'Create Dataset', the Teamcenter will create an empty dataset for all the CAE tools. The sub-menu 'Launch Session', will prompt the user with the user interface to select only the required CAE tools and the location in the local user machine to download the empty datasets for the selected CAE tools as shown in Fig. 3. In general, only a few of the listed CAE tools will be used for any particular CAE simulation studies. Hence, downloading the datasets of all the CAE tools may not be required. Thus, enabling the user to download the datasets of selective CAE tools helps in reducing the overall number of datasets, making data management simpler. One sample screenshot for the downloaded dataset in the local user machine is shown in Fig. 4. Once the empty datasets are downloaded to the local user machine, users are allowed to work on these datasets through the respective CAE applications. Upon completion of CAE tasks, the user needs to select the sub-menu called 'End Session' so that only the non-empty datasets will be imported into the Teamcenter CAE folder and all the datasets from the local machine will be deleted automatically.

The implementation of CAE simulation processes being practiced at the division calls for the customization of Teamcenter application. These customizations include creating Simplified CAD items from the existing CAD items, creating CAE items for the corresponding Simplified CAD items, and integrating the High-Performance Computing (HPC) server with the Teamcenter application to carry out simulation runs. In general, the geometric details of the CAD part/assembly will be simplified for CAE simulation studies. Thus, the simplified geometric details are associated with the simplified CAD item and carry the referred CAD part/assembly number in the item name itself for easy data management. Teamcenter application is customized with the main menu called 'Part Number' which has three sub-menus called 'CAD Item', 'Simplified CAD Item', and 'CAE Item' as shown in Fig. 5. The submenu 'Simplified Item' under the main pull down menu 'Part Number' will provide a user interface window to create the new Simplified CAD item as shown in the Fig. 6. Simplified CAD item id will carry their reference CAD model sixteen digit number with a 4 letter prefix like 'CAE ' and will also be having its own revision id. The default revision is '0' and then followed by alphabets like 'A', 'B', etc. The submenu 'CAE Item' under the main pull down menu 'Part Number' will provide a user interface window to create the new CAE item. CAE item name will carry the reference simplified CAD part number including the revision id, simulation process tag for which the files are being used and simulation process related attributes, etc. Certain process titles are predefined like F-Fuselage, W-Wing and M-Miscellaneous, etc. The first letter in the process title like 'F', 'W' and 'M', etc. are considered as simulation process tag in the CAE item naming system. Each of these process titles are predefined with certain attributes like FE Mesh, FE Model, etc. If the predefined attributes could not meet the

required specification, then user can define the new process attribute as shown in the Fig 7.

In general, CAE simulation runs are submitted at individual user machine and high-performance computing servers. Teamcenter application is customized to adopt both these approaches for submitting simulation runs. The first approach requires the users to download the required CAE files into the user machine and then submit the simulation runs manually. The second approach allows the users to directly submit the simulation runs on the high-performance computing server integrated with the Teamcenter application using the customized menu called 'HPC'. The main menu 'HPC' has three sub-menus called 'Start Session', 'Check Status', and 'End Session' as shown in Fig. 8. The sub-menu 'Start session' provides a user-friendly interface allowing the users to select appropriate CAE solvers and the hardware resources (number of nodes, cores and memory) as shown in Fig. 9. Once the simulation run is submitted from the Teamcenter application, the relevant data are transferred to the high-performance computing server and the execution starts if the resources like solver license, cores, etc. are available. If the required resources are unavailable, the simulation run will be in queue. The sub-menu 'Check status' provides information on the submitted simulation run status like 'waiting', 'executing', or 'completed'. After completing the simulation run, the user needs to select the sub-menu 'End session' which uploads the relevant output files from the high-performance computing server into the Teamcenter CAE folder.

In general, the steps followed in customizing the Teamcenter application for the in-house CAE Simulation process and data management are as follows.

- Installation of Interactive Development Environment (IDE) tools like Eclipse.
- Installation of Java 1.7
- Creation of a Java project in Eclipse for each specific requirement, like Simplified CAD creation from CAD part.
- Add dependency for JRE and Teamcenter application plugins.
- Divide the entire requirement into sub-requirements.
- Creation of Java program for each specific sub-requirement.
- Creation of User Interface (UI) based on the requirement, this includes the creation of text fields, buttons or select field.
- Creation of code for event handling like button click, text-changed or option value changed from the select field.
- Data fetching from Teamcenter application to customized code.
- Verification of user input data in the user interface form.
- Menu and submenu creation.
- Project Compilation, Testing and deployment to Teamcenter plugins.

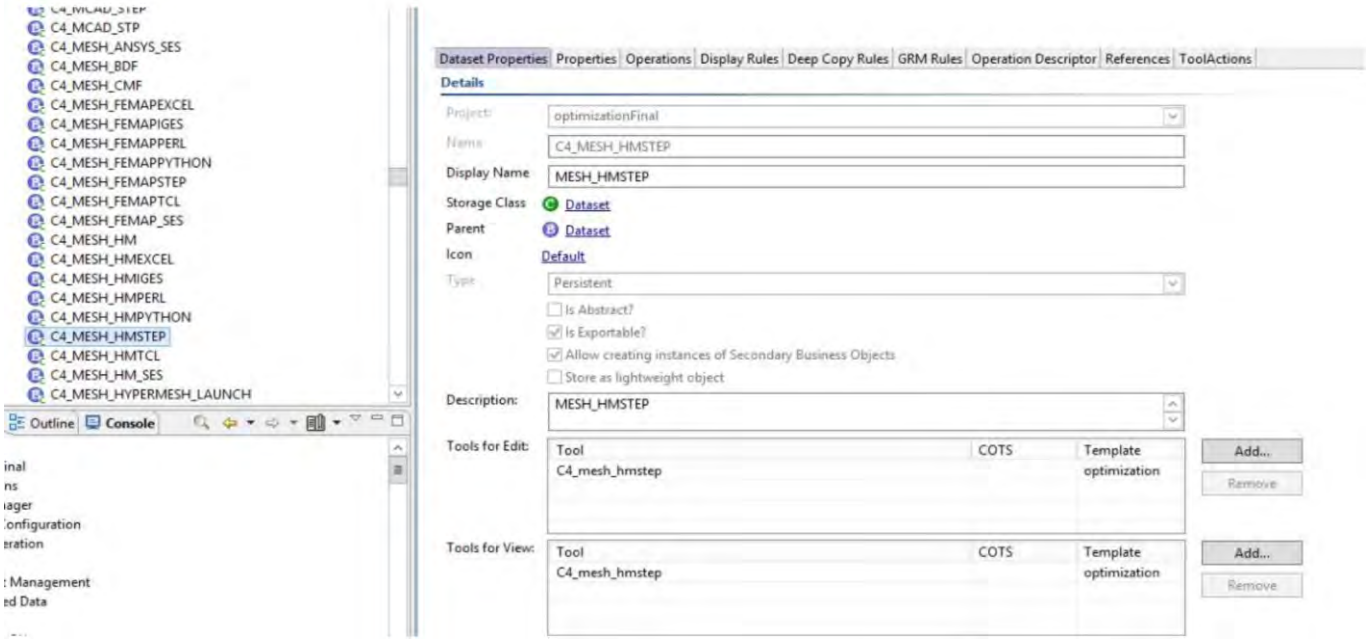

Fig. 1. Typical dataset configuration in BMIDE

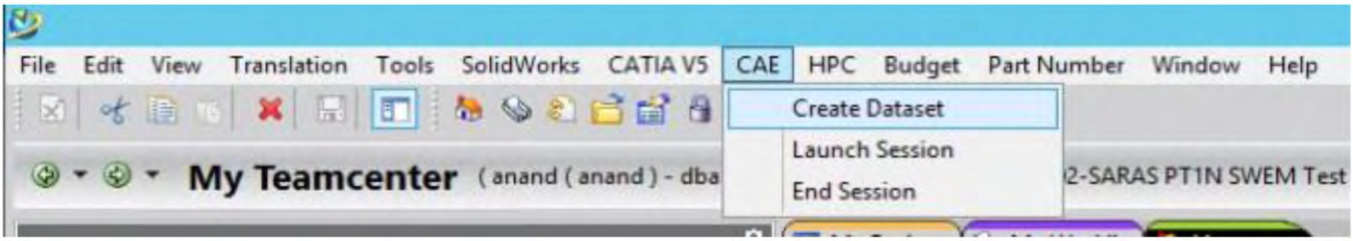

Fig. 2. Configured CAE menu and sub-menu

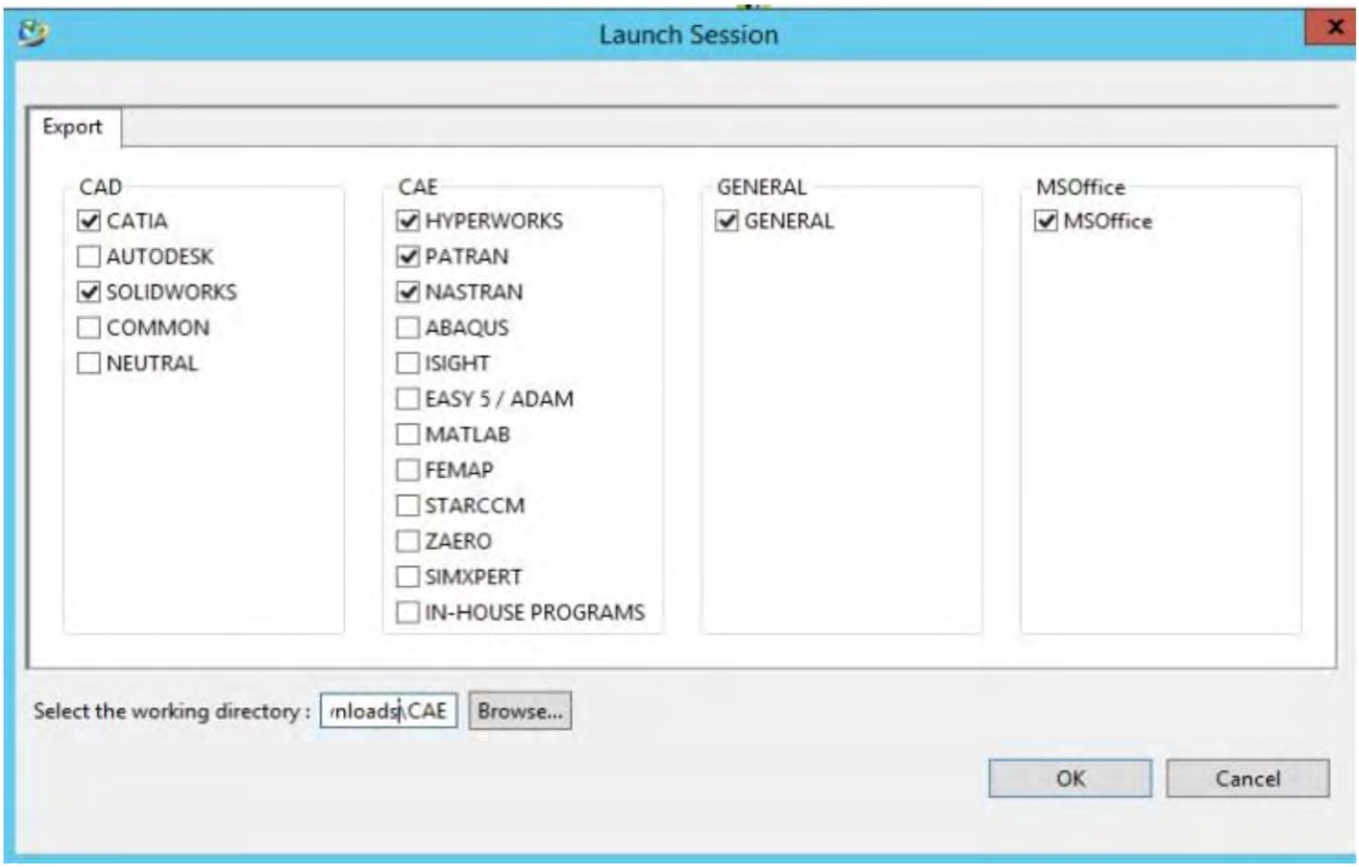

Fig. 3. Typical export CAE data to local user machine using the sub-menu Launch session

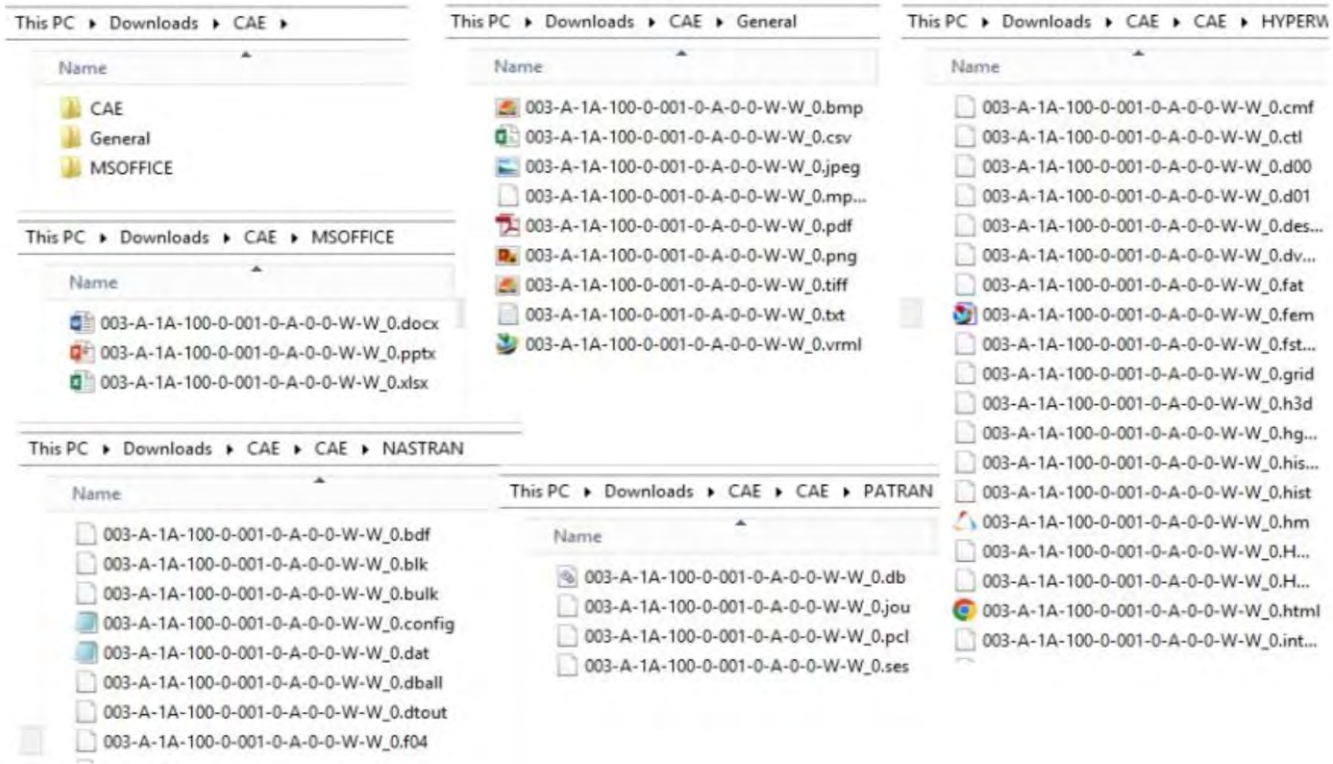

Fig. 4. Typical downloaded datasets in user machine

Fig. 5. Customized menu for simplified CAD item and CAE item

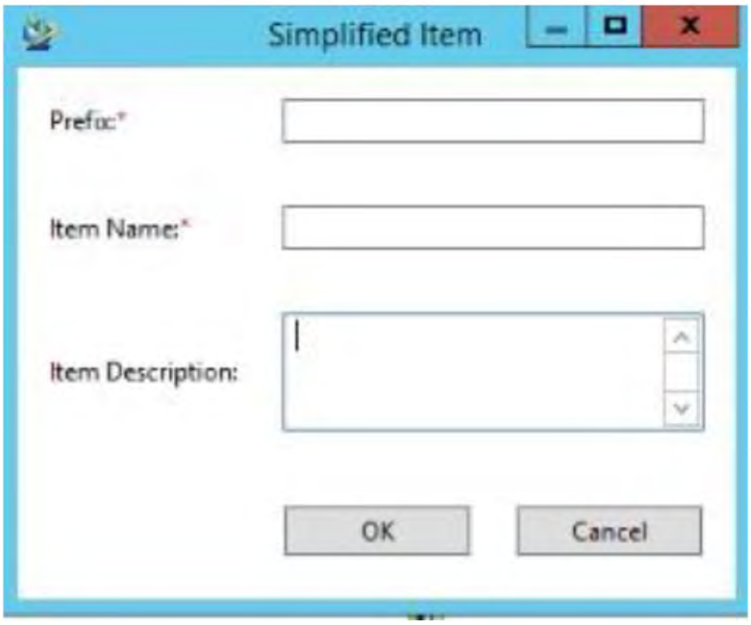

Fig. 6. User interface for simplified CAD item creation

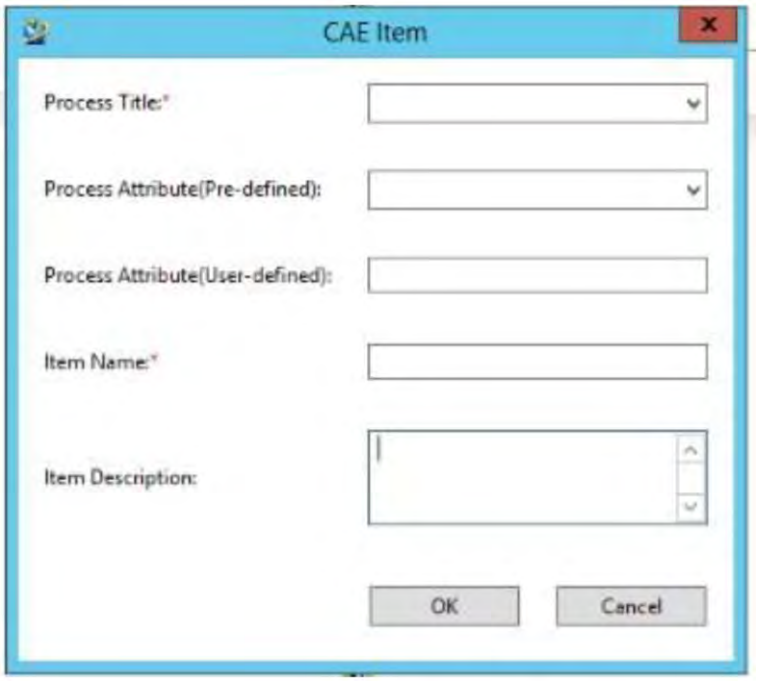

Fig. 7. User interface for CAE item creation

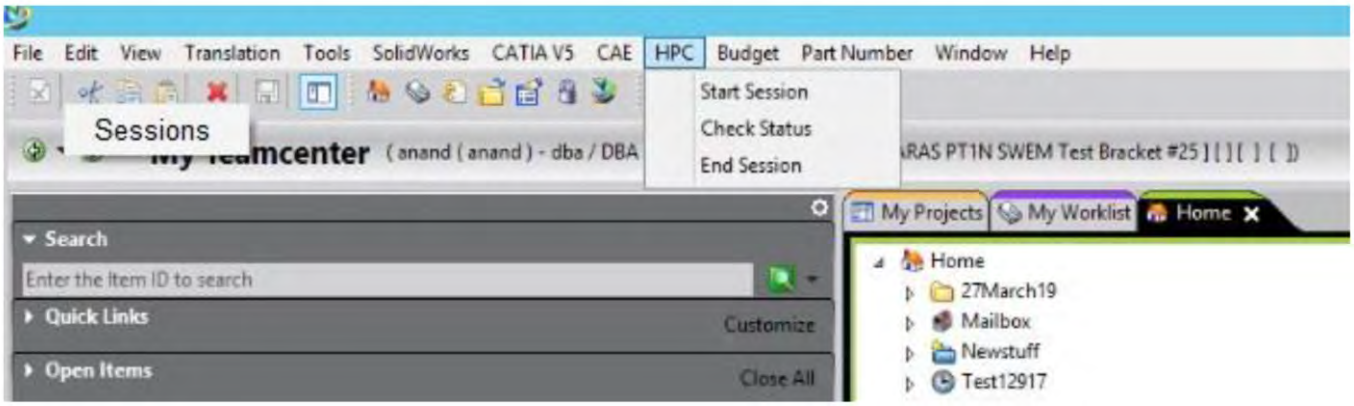

Fig. 8. Customized menu for HPC Integration

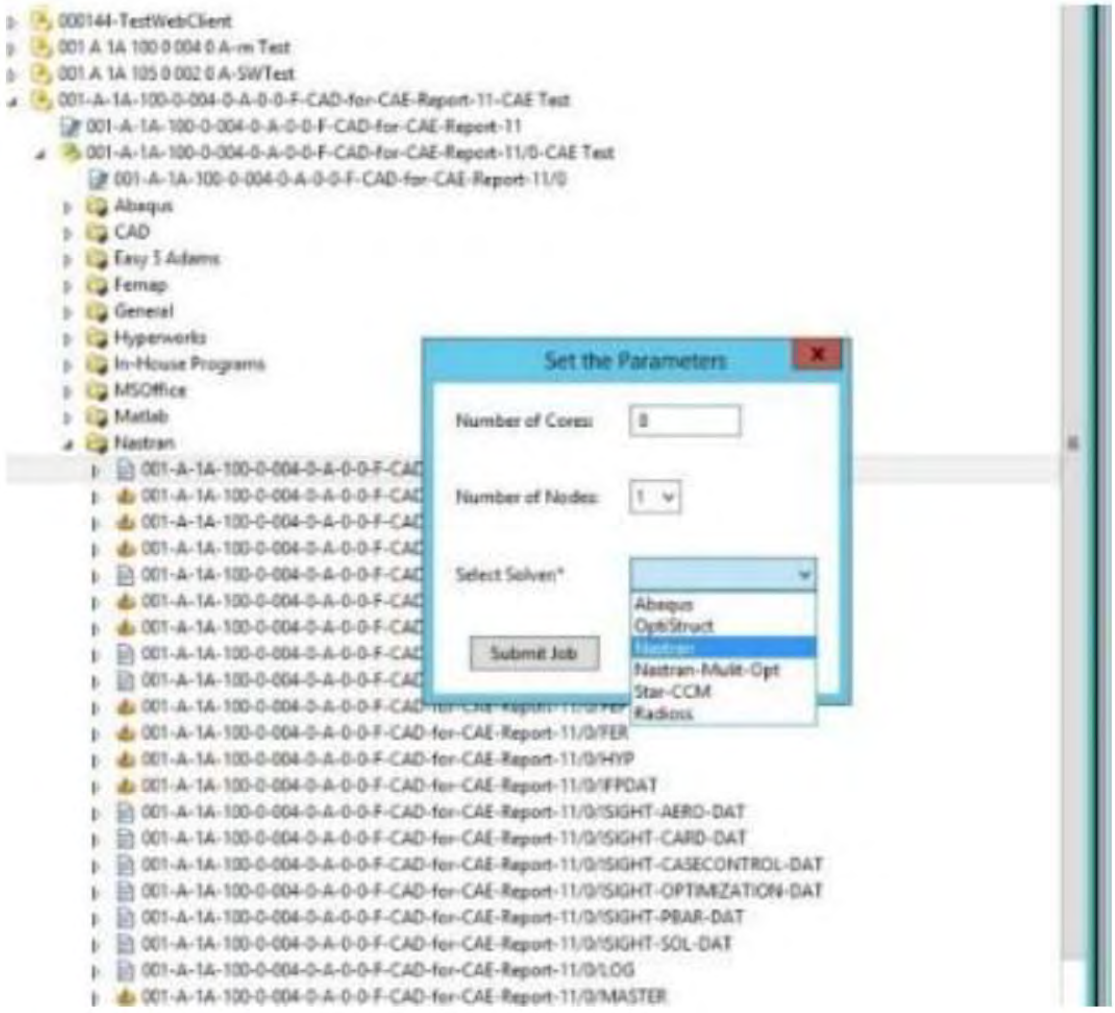

Fig. 9. User interface for start session for simulation in high-performance computing server

CONCUSION

Proposed and implemented the unique concept of computer-aided engineering simulation data and process management by configuring and customizing the Teamcenter application so that "as-analyzed" represents "as-designed".

ACKNOWLEDGMENT

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[2] Teamcenter 10.1 Help Library

Enhancing Requirements Engineering: Syntactical Writing and Data Modeling for Improved Aerospace Systems Development

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Abstract - This paper highlights the importance of requirements engineering in product development and the benefits of utilizing syntactical requirements writing and data modeling techniques. Clear and well-defined requirements are essential throughout the product development lifecycle, ensuring stakeholder satisfaction and project success. This paper emphasizes the significance of good requirements characteristics, such as completeness, consistency, verifiability, etc. It will show the application of The Ron Carson requirement structure method that provides a structured approach to syntactical writing, aiding in clear and unambiguous requirements expression. It shall also address the importance of requirements writing patterns in enabling effective System Modeling while maintaining traceability. Data modeling, based on industry best practices, facilitates the formalization of requirements, and assists in identifying gaps or clarifications. By combining syntactical writing and data modeling, this paper represents an industry application of enhancing requirements quality, documentation, reusability of formalized semantics, and improve consistency, leading to more effective product development.

Keywords - Requirements Engineering, Requirements Syntax, Systems Engineering, System Development, Product Lifecycle, Requirements Management

I. INTRODUCTION

In modern product development, the role of requirements engineering, and management has become increasingly crucial. The complexity of contemporary products, such as aircraft, demands a structured and disciplined approach to capturing, analyzing, and managing requirements. Without a systematic process for requirements engineering, projects often face challenges related to scope creep, unclear objectives, and a lack of alignment between stakeholders. Especially in industries like aviation, compliance with industry regulations and certification standards is of paramount importance. Ensuring that all requirements align with the necessary certification criteria are demanded for obtaining the necessary approvals and ensuring the safety and reliability of the final product.

Also, confidence in the system being designed is essential for stakeholder trust, risk mitigation, compliance, and achieving business goals. Early validation by means of Development testing reduces errors and aligns with industry standards. Continuous improvement is fostered through feedback obtained from V&V activities involving breaking down Requirements into specific, measurable criteria for operational testing and

maintaining traceability to ensure all requirements are validated.

Despite thorough efforts in defining requirements, there might be instances where certain aspects cannot be defined early in the requirements engineering phase and must be overlooked or not adequately addressed till some maturity is gained for system understanding. Identifying these gaps and omissions i.e., "if we've missed anything" early in the product development lifecycle is essential to avoid costly rework, improve stakeholder satisfaction, and enhance project success rates.

In the case of aviation, ARP4754A Guidelines for Development of Civil Aircraft and Systems, a well-established guidance document for the development of aircraft systems, clearly demands requirements traceability, system verification plan, RVTM or Requirements Verification and Traceability Matrix among other artefacts. The guidelines document deems such artefacts essential for ensuring the safety and airworthiness of aircraft. This clearly shows how effective requirements engineering coupled with data modelling techniques, and syntactical methods can help in achieving an aircraft architecture that aligns with the recommendations of ARP4754A, thereby contributing to the overall safety and quality of the aircraft.

This paper provides an overview for a requirement engineering approach as applied for an aerospace system development lifecycle. It proposes a systematic approach to elicit requirements, manage requirement changes, manage workflow, and maintain traceability for requirements. The intent is to keep the requirements relevant and streamlined throughout the product development lifecycle starting from conceptualizing to V&V activities as development programmes of aerospace systems can be complex and more often go on for years. The methodology followed connects the technical and management processes defined in ISO/IEC/IEEE 15288:2015 Systems and software engineering — System life cycle processes and requirements engineering processes defined in ISO/IEC/IEEE 29148:2018 Systems and software engineering — Life cycle processes — Requirements engineering with the objectives defined in ARP4754A. Copyright © 2023 BlueKei Solutions Private Limited

II. REQUIREMENTS ENGINEERING FOR SYSTEM OF INTEREST

A. Scope of Requirements Engineering

Product Development as requested by a stakeholder, internal or external to the organization, leads to identification of scope and system of interest for the organization. The scope of requirements engineering depends on if the project is a totally new product (greenfield) or if modification of an existing product (brownfield). Either case would demand to objectively implement and prove that system provides for the stakeholder request. To objectively implement is to prove if the system is built right, also known as System Verification. While to objectively prove that system provides for the stakeholder request, which can also be evolving throughout the development cycle, is to prove if the built system is the right system, also known as System Validation. Considering that the stakeholder request can sometimes be too vague or even too detailed, there comes a need to fully understand the request of the stakeholder. For translating the request for implementable action items for the engineering teams, requirements are needed.

B. Requirements for an Aerospace System

For this case study, the High-Level System Requirements, for an existing product, were initially audited for understanding the as is state. The intent was to gain confidence on the completeness of the defined requirements to ensure smoother path to certification by identifying missing gaps, improving verifiability, and ensuring completeness. The approach was to understand the effect of missing requirements to ARP 4754A objectives.

The findings from the audit are listed below:

- The lack of structured requirements engineering process contributes to the problem. With a revolving door of personnel—some working

on existing requirements and others starting from scratch—consistency becomes a challenge. The absence of a standardized approach leads to redundancy, rework, and increased development time, impacting overall productivity and hindering project progress. The organization faces challenges due to a limited or primitive understanding of requirements engineering. This lack of awareness includes concepts such as distinguishing between needs, stakeholder requirements, and system requirements. The absence of a clear hierarchy and classification of requirements leads to confusion and difficulties in capturing the true essence of what the product should achieve, affecting the quality of the final product.

- Major gap lies in the inadequacy of existing requirements practices, characterized by unstructured, non-syntactical writing, lack of traceability, multiple interpretations, absence of a management framework for digitized requirements, and inefficiencies in requirements elicitation, modeling, and management. One of the fundamental issues is that many existing requirements were documented without following a structured or syntactical format. This lack of standardization can lead to ambiguity and confusion, making it challenging for stakeholders to understand and interpret the requirements consistently. Due to the absence of a clear and standardized format, different stakeholders may interpret the requirements differently. This lack of a single, agreed-upon interpretation can result in misunderstandings, conflicting expectations, and delays in product development.

The International Council on Systems Engineering (INCOSE) provides guidelines for writing good requirements, which include characteristics such as completeness, consistency, verifiability, etc. Many existing projects might not be fully aligned with these guidelines, leading to potential ambiguities, conflicts, and inefficiencies during the development process.

The study will explore how techniques like The Ron Carson requirement structure method along with INCOSE's recommendations and guidelines can aid in uncovering and addressing such gaps and illustrate how such alignment can improve project outcomes, emphasize the role of requirements engineering in achieving compliance with relevant certification processes and guidelines.

III. METHODOLOGY AND RESULTS

In this paper, the first step is to identify the system as a black box that is for the initial system understanding to gain a bird's eye view for the system of interest. Being specific to aerospace systems, such as an aircraft, or its subsystems, are often constrained by regulatory or certification authorities.

INCOSE proposes requirements definition starting from "Integrated Set of Needs" to "Design Input Requirements" for any product development refer [6]] . As per INCOSE, needs can be elicited from various stakeholders that get involved in different lifecycle stages of the product as per the V-Model. Refer [6] Once needs are gathered from a comprehensive list of concerned stakeholders as "Integrated set of needs," they can be transformed into "Design-Input Requirements" which are well-structured textual statements that conform to the following structure: [Entity] [shall/should] [to WHAT] [HOW WELL] [under what CONDITIONS].

This is an initial step to requirements engineering for any system. Towards a systematic implementation of requirements engineering for an aerospace system, this paper emphasizes Problem Domain – Solution Domain methodology for requirements analysis for deriving the system requirements from stakeholder needs. Problem Domain would comprise of Stakeholder Needs analysis where in the regulatory and certification authorities' requirements are also stakeholder needs. The figure below depicts the transition from stakeholder needs, stakeholder requirements [problem domain] to system requirements and further lower-level requirements to component level. [solution domain]

Stakeholder needs from various sources, captured as is, can be analyzed for identifying the main

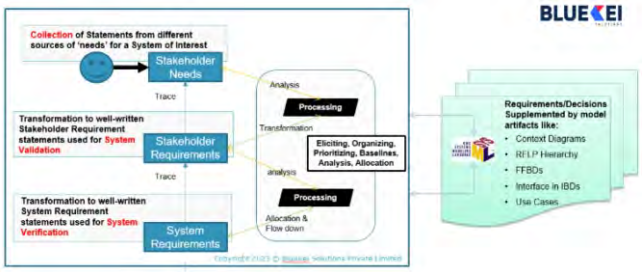

Figure 1: Holistic Requirements Engineering View

objective or "problem statement" that requires the development of the system. Such statements, if required, can be transformed into stakeholder requirements that could conform to a specific structure pattern or syntax. [Refer: [6]] With this step, the areas that require more clarity from the stakeholder can be identified. Hence, stakeholder needs statements are refined stakeholder needs that specify 'what' is expected of the system by a stakeholder. Such a document contributes to systematic reduction in ambiguity for elicited stakeholder needs. Once the stakeholder requirements have gained consensus with the concerned stakeholder, further engineering activities can be initiated to transition to solution domain, beginning with the definition of system requirements. The difference between the stakeholder requirements and system requirements is that the system requirements specify 'what' is expected of the system of interest. It can be noted here that as the system of interest is relative, the high-level system of interest once decomposed to further layers, the system of interest will change for different teams. The activities mentioned below can be common to various levels of requirements in the requirements hierarchy.

A. Requirements Synctactical Writing

Structured or syntactical writing is required in requirements engineering because it helps to ensure that the requirements are:

- Complete: All necessary information is included in the requirements.
- Consistent: The requirements do not contradict each other.
- Unambiguous: The requirements have a single, clear meaning.
- Verifiable: The requirements can be objectively tested to determine whether they are met.
- Traceable: The relationships between different requirements can be easily identified.

These qualities are essential for ensuring that the requirements are accurate, reliable, and can be implemented successfully. Here are some specific examples of why structured or syntactical writing is needed in requirements engineering:

To avoid ambiguity, the requirements should be written in a clear and concise manner. For example, the requirement "The system shall be easy to use" is ambiguous because it does not specify what makes a system easy to use. A better way to write this requirement would be "The system shall have a user interface that is intuitive and easy to navigate."

To ensure consistency, the requirements should use the same terminology throughout. For example, if the requirement "The system shall provide a login screen" uses the term "login screen," then all other requirements that refer to this feature should also use the term "login screen."

To make the requirements verifiable, they should be measurable. For example, the requirement "The system shall be able to process 100 transactions per second" is verifiable because it is possible to measure the number of transactions that the system can process per second.

To improve traceability, the requirements should be numbered and organized in a logical way. This will make it easier to identify the relationships between different requirements.

The basic structure of a structured functional requirement as per Ron Carson (Ref [2]) is as follows:

- Agent: The product or service entity which has the required characteristic or performs the intended function.
- Shall: Indicates that the statement is a mandatory requirement.
- What: The function that describes what the agent does that is observable at its boundary,

or another mandatory characteristic or attribute of the agent (e.g., size, color).
- How well: The measurable characteristic of the function or a design attribute. This is the performance attribute and includes timing of the function.
- Under what conditions: These addresses two specific considerations:
- Conditions: The modes, states or environmental conditions that are present when the agent performs its function or has the stated property.
- Inputs: The triggering or initiating events, observable at the boundary, that cause the agent to perform the function.

For example, a structured requirement for a car might be:

The car shall accelerate from 0 to 60 mph in 6 seconds.

In this example, the agent is the car, this shall indicate that this is a mandatory requirement, the what is the function of accelerating from 0 to 60 mph, the how well is the performance attribute of 6 seconds, and the under what conditions are the environmental conditions of the car being on a level surface and not being obstructed.

1) Architectural elements segregation:

Writing requirements syntactically aids in identifying and segregating architectural elements in the following ways:

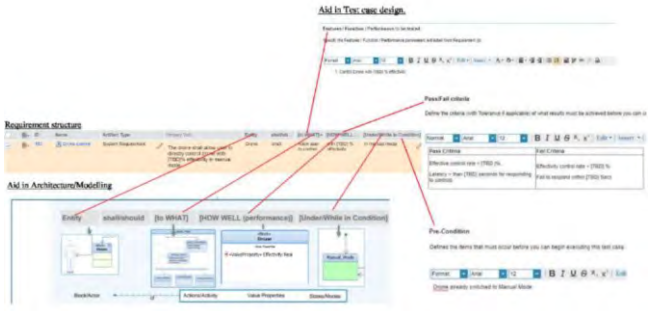

Figure 2: Connecting Requirements to Architecture and V&V

Clear Entity Definition: Structured requirements specify the "Agent" or entity explicitly, ensuring a precise definition of architectural elements like systems, components, or modules. This clarity enables stakeholders to distinguish different architectural entities easily.

Functional Decomposition: The "What" aspect of requirements articulates the capabilities, functions, and scenarios of the entity. This breakdown facilitates the decomposition of architectural elements into their functional components, aligning with SysML's representation of functions and activities.

Quantifiable Attributes: Expressing "How well" characteristics as measurable attributes helps in quantifying architectural performance. These attributes can be directly mapped to SysML (Systems Modeling Language) properties, allowing for a quantifiable analysis of architectural elements.

Behavioral States: Describing "Under what conditions" helps in identifying the states and modes of operation for architectural entities. These conditions align with SysML state machines, making it easier to represent and analyze the dynamic aspects of architectural elements.

2) Identifying Types of requirements:

Syntactical writing employs standardized grammatical patterns for various requirement types, aiding in their categorization and verifiability (of type of requirement):

Functional/Performance Requirements: These specify how an agent (system or component) should function in relation to input and output interfaces, performance levels, and timing under specific conditions. This syntax helps ensure that functional and performance aspects are clearly defined and measurable.

Functional/Performance - The AGENT shall FUNCTION in accordance with INTERFACE-OUTPUT with PERFORMANCE [and TIMING upon EVENT TRIGGER in accordance with INTERFACE-INPUT] while in CONDITION.

Design Requirements: Design-related requirements focus on exhibiting specific design con-

straints, often tied to performance, while considering certain conditions. This syntax ensures that design-related criteria are welldocumented and aligned with project goals.

Design - The AGENT shall exhibit DESIGN CONSTRAINTS [in accordance with PERFORMANCE while in CONDITION].

Environmental Requirements: These requirements detail an agent's behavior or characteristics during or after exposure to environmental conditions, including exposure duration. The syntax facilitates the clear description of environmental dependencies.

Environmental - The AGENT shall exhibit CHARACTERISTIC during/after exposure to ENVIRONMENT [for EXPOSURE DURATION].

Suitability Requirements: Suitability requirements address an agent's suitability for specific conditions and performance expectations, while considering condition duration. This syntax ensures that suitability criteria are defined and measurable.

Suitability - The AGENT shall exhibit CHARACTERISTIC with PERFORMANCE while CONDITION [for CONDITION DURATION].

3) Improve the verifiability

Syntactical writing plays a crucial role in enhancing the verifiability of requirements by establishing clear relationships between different elements of the requirement statements. Here is an elaboration of how these relationships contribute to improved verifiability:

Pass/Fail Criteria (How Well): In syntactical writing, the "How well" aspect of requirements specifies the criteria for success or failure. By explicitly defining the expected performance, accuracy, or other measurable attributes, it becomes easier to objectively assess whether the requirement has been met. This linkage ensures that verification activities can be conducted with precision, allowing stakeholders to determine if the system complies with the specified criteria.

Pre-Conditions (Under What Condition): The "Under what condition" aspect addresses the circumstances or prerequisites necessary for the requirement to apply. Linking pre-conditions to requirements clarifies when and under what circumstances the requirement should be validated. Verifying pre-conditions ensures that the system operates in the expected context, which is essential for accurate verification.

Features/Functions/Performance (What): The "What" aspect of requirements defines the features, functions, or performance characteristics expected from the system or component. By clearly specifying these elements, syntactical writing provides a precise description of what needs to be tested or validated. This clarity helps verification teams understand the scope of their work, making it easier to devise test cases and evaluation criteria.

B. Requirements Validation

Requirements are key factors as they drive the lifecycle of a project, it is essential that they are Clear & concise, if not, they can be interpreted in many ways and the project objectives can get derailed. Similarly, when requirements lack clarity and structure, it becomes challenging to determine if they are verifiable. This uncertainty hinders effective Verification and Validation (V&V) activities, making it difficult to assess whether requirements written is implemented accordingly or not. Verification and validation are one such stage to be impacted due to the ambiguity. Clear and concise requirements bring out “what” to be tested, “how well” & and “under what conditions” the test need to occur. This information is critical during the Design of experiment to verify or validate the requirement as it spills light on what is exactly expected, ambiguity amongst any of these can cause the V&V team to invest much of their resources to test what is not actually required in the first place, which adds up to increase in resource of Time & cost.

Without a traceability mechanism, it becomes difficult to trace between requirements, design

elements, and verification activities. This lack of traceability can make it hard to ensure that all requirements are met and that changes are effectively managed. In the age of digital transformation, requirements are often managed electronically.

Requirement validation is a process of ensuring that all the characteristics of a good requirement are met, while there are various methods to employ and ensure for the process with stakeholders to ensure objectives are met. The importance of this is reflected in driving further stages of the development process such as: Architecture and V&V processes.

Any inconsistency in either of the characteristics affects the other verticals. A requirement not meeting any of the characteristics impacts resources such as cost and time in the further stages. Hence "Early validating" requirements before baselining and floating for other departments for further development and testing should be ensured. while multiple stakeholders aid in this process. To proceed with validating and verifying a requirement, a method(s) must be chosen. Several SME's/Higher engineering teams contribute to identification of Method of Verifying and validating a requirement by means of a matrix called RVTM as per ARP Objective [5.5.7.4 & 5.5.6.3]. It is ensured that each requirement has a defined method for it to say it is verifiable. ARP4754A mentions potential validation methods for any requirement. For the

- MBRE (Model Based Requirements Engineering): Requirement modelling, particularly Model-Based Requirements Engineering (MBRE), enhances requirements' clarity and structure by creating detailed graphical models representing relationships, dependencies, and system elements. MBRE provides a systematic approach to requirements development. The need for MBRE arises from its benefits:
  - Incompleteness Detection: MBRE helps detect incomplete requirements, making gaps or ambiguities more visible due to visual representation.
  - Gap Analysis: It facilitates gap analysis by comparing models of expected system behavior with existing requirements, ensuring comprehensive coverage.
  - Validation: MBRE enables effective requirement validation through simulation, identifying issues early in development.
  - Clarity and Precision: Models offer a visual, structured representation, improving understanding and communication among stakeholders.
  - Traceability: MBRE enhances traceability between requirements and system components, aiding change management.
  - Documentation: Models provide organized, accessible documentation, particularly beneficial for complex systems with numerous requirements.
- Analysis: A wide range of analysis techniques could be employed to determine acceptability of a requirement, Including Safety analysis which can be confirmed with regulatory authorities on applicability & various other analysis are used such as: Use case analysis, Risk analysis, Dependency analysis etc. The resultant of these analysis provides insights on whether a requirement written is:
  1. elaborating the intended use case - which confirms the "Necessary & Traceable characteristics"
  2. Risk analysis gives insights on "Feasibility" etc.
- Test: Development test and evaluation (DT&E) is planned for special tests or demonstration for validating requirements. This activity can occur in parallel while writing requirements as part of Early validation of requirements in case of a "New system" to be introduced. The testing is carried out to verify the behavior, confirm the parameters written are relevant and are "Feasible" T&E confirms Feasible and verifiable characteristics of a requirements.
- Similarity (Experience): This mode of validation is applicable when certain requirements are to be reused from a system which is already certified and has satisfactorily completed its lifespan, This method is applicable only if : Legacy data is available and The system under development matches with system which

already exists in terms of: Function, Failure condition and operating environment, upon which the credit can be taken. This confirms all characteristics of a requirement since it already exists.

- Engineering review: The review process is usually contributed by inspections and demonstrations to conclude on the validity of a requirement. usually consisting of all the stakeholders concerned, where the requirements are read and based on the history of development of such systems (if any) the characteristics are confirmed. Usually, the Engineering review is the most employed technique. Since the respective domain engineers confirm all the characteristics and acknowledging with a sign off to conclude on validation with rationale.
- Traceability: Traceability to source is essential to be validated before implementing any requirement. This could also ensure that the requirement is necessary, transformed at an appropriate level, and also traced to dependent peer requirements.

C. Requirements Traceability

A well-executed system of tracing artifacts can provide valuable insights into the development process and help us better understand the system, assess its impact, and make efficient use of existing artifacts. This traceability system can be divided into two main parts: horizontal and vertical relationships, and pre- and post-traceability. Horizontal relationships involve connections between artifacts of the same type, such as relationships between different requirements. On the other hand, vertical relationships describe how an artifact relates to several types of artifacts, like the link between a requirement and a system component. This second dimension includes pre- and post-traceability, which are also called forward and backward traceability. Pre-traceability focuses on how requirements are linked to their sources, such as stakeholders or use cases. Post-traceability, on the other hand, deals with the connections between requirements and artifacts created in later development stages, like component specifications or interface definitions.

Common traceability links between requirements and model elements can be described through four key relationships:

- Derive: This link signifies that a model element has been derived directly from a specific requirement. It demonstrates a clear connection between the requirement and the resulting model representation. For example, a system architecture diagram may derive from high-level system requirements, showing how those requirements are translated into a technical design.
- Refine: The refine link indicates a hierarchical relationship where a model element refines or provides more detailed information about a higher-level requirement. This helps in breaking down complex requirements into smaller, more manageable components. For instance, a detailed use case diagram can refine a broader functional requirement, providing a more granular view of system behavior.
- Satisfy: When a model element is linked to a requirement with a "satisfy" relationship, it means that the model element fulfills or meets the specified requirement. This connection ensures that the model faithfully implements the requirement's intent. For example, a detailed software component diagram may satisfy the requirements related to specific system functions.
- Trace: The trace link is a broader connection that signifies a general association between a requirement and a model element. It does not imply derivation, refinement, or satisfaction but rather serves to document the association itself. It is often used when there is a loose or indirect connection between a requirement and a model element, helping maintain transparency in the traceability matrix.

D. Requirements Management

Some of the aspects of requirements management that were considered for this study are as follows:

- Defining Roles and Assigning Responsibilities: Clearly defining the roles and responsibilities of individuals or teams involved is a

crucial step in the requirements management process. This typically includes roles such as the "author" who creates the initial requirement, the "reviewer" who assesses the requirement for correctness and completeness, and the "approver" who gives final approval. Defining these roles ensures that each aspect of requirement development is overseen by the appropriate parties, leading to well-structured and reliable requirements.

- Prioritization: involves assigning a level of importance or urgency to each requirement. This allows project teams to focus on addressing the most critical requirements first, ensuring that limited resources are allocated effectively. Prioritization is essential for delivering valuable features or functionalities early in the project timeline.
- Change Management: Dealing with changes to requirements involves establishing a formal process for requesting, evaluating, approving, and implementing changes to requirements. Proper change management should ensure that any modifications to requirements are carefully considered and documented to prevent scope creep and maintain project integrity.
- Status of the Requirement: This aspect involves maintaining a clear record of the status of each requirement throughout its lifecycle. Common statuses may include "draft," "under review," "approved," or "rejected." Tracking the status of requirements helps stakeholders understand where each requirement stands and allows for effective communication and decision-making
- Status of Implementation of the Requirement: monitoring this aspect of requirements involves assessing whether the requirement has been fully or partially implemented, is in progress, or has yet to be started. Monitoring implementation status ensures that the project stays on track and that requirements are being realized as intended.
- Matrix View:
  - Coverage Matrix: It helps assess the coverage of requirements, indicating which parts of the system are addressed by specific requirements. It ensures that no critical aspects are overlooked.
  - Traceability Matrix: This matrix establishes traceability between various elements of the project, such as requirements, design components, test cases, and even source code. It helps ensure that each requirement is properly implemented and tested, providing a clear path to trace a requirement through its lifecycle.
  - Validation Matrix: This matrix defines the criteria and methods for validating each requirement. It specifies how each requirement will be tested or verified to ensure it meets the intended functionality. The validation matrix is crucial for confirming that the system works as expected Be aware of the different meanings of the homophones “affect” and “effect,” “complement” and “compliment,” “discreet” and “discrete,” “principal” and “principle.”

These are some aspects of requirements management that were considered for creating, managing, and tracking requirements effectively, ensuring that projects are wellstructured, adaptable to changes, and successful in meeting their objectives.

E. Requirements Meta Modeling

The concept of metamodeling was utilized to create a standardized representation of the problem domain, capturing essential concepts, relationships, and constraints relevant to the product. This metamodel served as a foundation for managing the requirements and guiding the development process towards meeting the intended objectives. This template should include fields for clear identification, version control, authorship, and traceability to higher-level requirements. A structured template simplifies tracking changes and enables efficient management throughout the development lifecycle.

Requirements Management Tools can be used to combine the above-mentioned efforts in one place. Within tools, attributes can be used for

requirements that contribute to various aspects mentioned above. The specific attributes in the requirements management tool can be tailored as per need. However, the figure below depicts the aspects to consider for a requirement.
In conclusion writing requirements syntatically with aid of data model technique, contribute to enhanced verifiability and architecture development. This work delves into the vital area of requirements engineering and addresses significant challenges identified in an organization's processes. It highlights the organization's struggles with a lack of structure and inconsistent documentation, which have led to issues such as ambiguity, conflicts, and project delays. To tackle these challenges, the paper proposes implementing The Ron Carson requirement structure method and leveraging INCOSE's guidelines, emphasizing the importance of aligning with best practices in requirements engineering. It underscores the importance of structured syntactical writing in this process, which offers various advantages such as completeness, consistency, unambiguity, verifiability, and traceability.

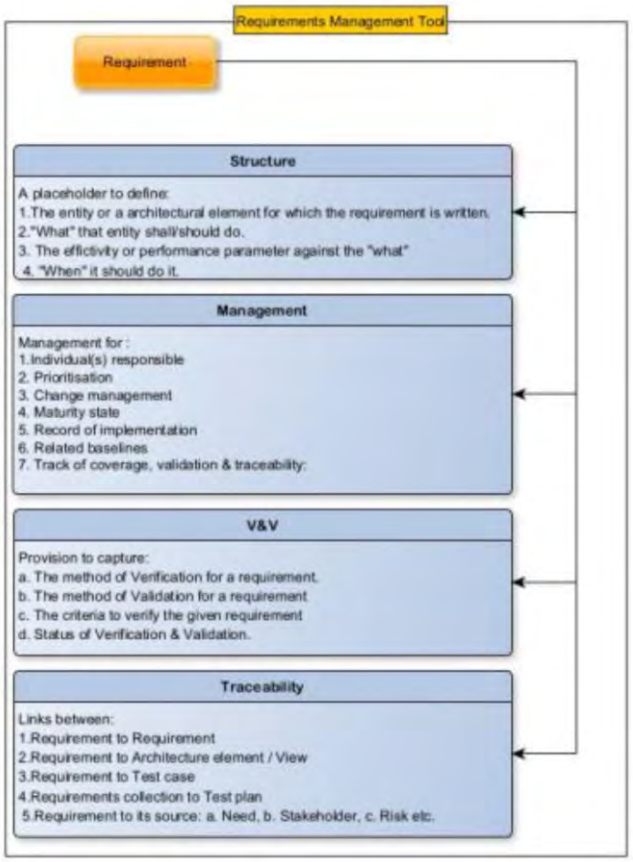

Figure 3: Pillars of Requirements Engineering

Additionally, we underline the pivotal roles played by requirements traceability, validation, and management. Effective traceability encompasses horizontal and vertical relationships, pre- and post-traceability, along with essential linkages like Derive, Refine, Satisfy, and Trace. Clear and concise requirements are fundamental for project execution, while their validation ensures adherence to the traits of robust requirements. Early validation, diverse validation methods, and Model-Based Requirements Engineering are advanced techniques that foster clarity and structure in requirements.

Lastly, requirements management encompasses the clear delineation of roles, prioritization, robust change management procedures, meticulous tracking of requirement statuses, and comprehensive matrix views, all culminating in wellstructured and adaptable projects that triumphantly fulfill their objectives.

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Structural Analysis of a Ship Using Simcenter FEMAP with NX Nastran

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Abstract - Achieving enough strength in a ship has long been one of the most difficult issues for ship designers since ships are complicated geometries that are subjected to a variety of loadings at sea, including hydrostatic, hydrodynamic, wind, wave, etc. The standards to assure compliance are provided by the International Maritime Organization (IMO) and classification societies to guarantee that the ship's strength is sufficient to withstand all demands throughout its service life. Thus, structural analysis is needed to assess the overall strength of hull, and the means in this regard are based on finite element method which may be applied either local or global aspect of the ship. This paper is an attempt to carry out the structural analysis of the ship in global aspect using Siemen's Simcenter FEMAP with NX Nastran software to locate the stress concentration and life of the ship.

Keywords - FEM, Nastran, Vessel, FEMAP, CAD, CAE

I. INTRODUCTION

The use of the Finite Element Method (hereinafter FEM) is a tool that allows to analyse and evaluate both the stresses and deformations that occurs in an element of study as a response of a load on it. This allows the Naval Design and Engineering team to perform evaluations of elements of a system, which in the case of this study, simulates the response of the structure and generates a tool for the designer to analyse the overall vessel under slamming pressures. In this way, the aim is that the vessel to be designed complies with the requirements established in the classification regulations ensuring the structural integrity of the vessel during its life cycle in the Operation Phase. While it is true that the rules of the various classification societies are guidelines for design, these aim for the structure to support the conditions of the ocean it will face and generates as a result the dimensions of the structural elements and all those elements that contribute to the structural integrity of the vessel. The vessel in this study was validated to comply with performance specifications such as speed, length and beam dimensions, for which the shapes were carried out through the use of design tools (CAD) and analysis (CAE) (Computer Aided Design- Computer Aided Engineering). This was an input in the subsequent implementation of structural analysis by the Finite Element Method with the use of numerical modelling. The process integrates the basic knowledge of surface handling and is complemented with the application of the different loads that affect the case study such as Slamming in the Wet Deck and Hull, Hydrostatic Pressure, Gravity and the Displacement of the Vessel. Within the development of this study, the mesh sensitivity analysis was carried out, which ensures the independence of the results of the mesh. Due to the above, and in view of the fact that FEM allows the analysis of irregular geometries such as the hull of a vessel, the application of loads, the handling of the system's boundary conditions and the numerical evaluation of the materials' behaviour, it can be established that it is a convenient tool to carry out the analysis of the present investigation and to observe the response of the vessel's structure.

II. STATE OF THE ART

A. About FEMAP with NX Nastran

Femap is a finite element modelling and post-processing environment. It interacts with solvers such as Nastran to model physical behaviour to

assist in the drawing of conclusions about said behaviour. Finite element solvers typically require strict text file-based formatting of your analysis setup, which is rarely done manually (by hand) anymore. Instead, programs such as Femap are used to prepare text file inputs to the solver using a combination of a modern graphical user interface built-in functions to automate what could otherwise be tedious and error-prone data entry tasks.

Nastran is a separate finite element solver product that can be bundled within Femap. Simcenter Nastran (formerly NX Nastran) is an actively-developed offshoot of the Nastran code base, but is one of the most common solvers for finite element analysis (FEA). Nastran is essentially the math behind FEA. As a pre-processor, Femap assists with building a model of a part, and then translates that into a Nastran formatted "input file". Nastran then computes the behaviour. Following this, Femap reads the results and provides interpretation tools to facilitate the processing of output data. Oftentimes, the amount of information from the model is substantial, and Femap can enable a more rapid understanding of gross behaviour.

B. Corvette type Vessel

For this study, understanding the conditions in which the vessel would be found was fundamental, therefore, the study of the slamming event is important in understanding that it is a transitory load that affects the structure of the vessel in its operation, evaluating this throughout its entire structure and validating the calculations enhanced in the studs, is a fundamental tool for any design process and testing of any vessel, allowing with it to validate that the process is suitable and responds to the objective of the present study. This process has shown that the structure supports the stresses and deformations allowed by the classification society, under real parameters that contribute to the knowledge of a design process and structural analysis of a Corvette type vessel and gives the possibility to perform other analyses in different load conditions where it is required to study the life of the vessel. III. VESSEL CHARACTERICIS AND MODEL SETUP

III VESSEL CHARACTERICIS AND MODEL SETUP

Fig.1. Corvette Ship Model

The vessel in this study has the general characteristics and weights was designed as shown in the General Arrangement Plan Fig. 2. Its mission profile is based on carrying out patrol operations in the Arabian sea, where the average wave height ranges from 1 meter to 5.56 meters according to statistics provided by the General Maritime Directorate.

A. Loading Conditions

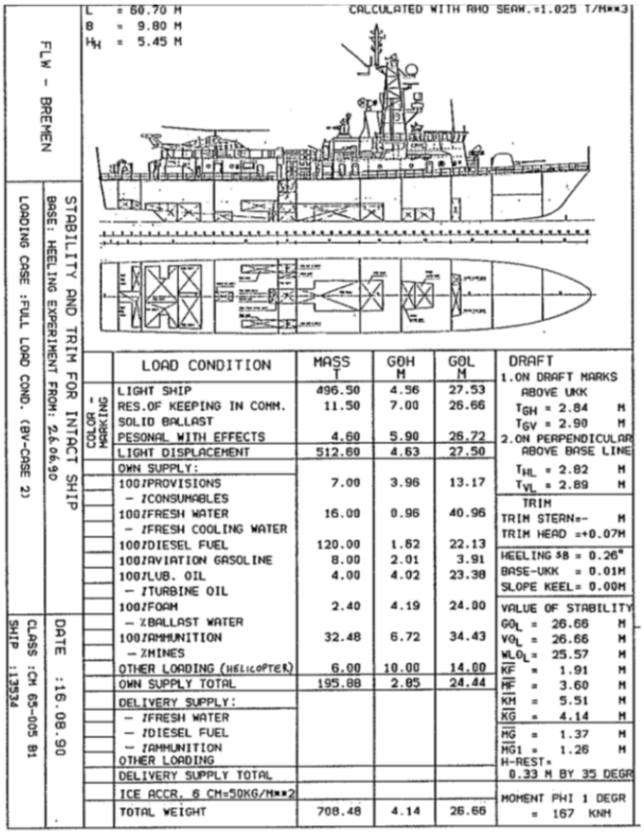

Fig.2. General Arrangement Plan and Vessel Tank Load & Storage Spaces

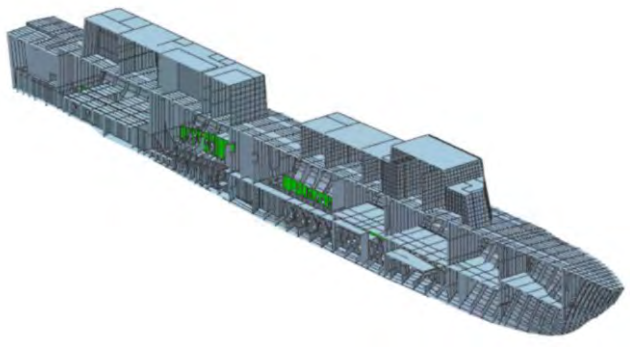

Fig.3. CAD Model of the Vessel

During the development of the analysis, the recommendations of the mentioned classification society were followed, for the application of the forces that act in the hull of the ship, which were divided in three different forces, characterizing the Hydrostatic Pressure with the design draught under full load, the pressure during the Slamming event and the standard acceleration due to gravity.

No.	Load case
1	Load case 1- Slamming pressure in compartment 1 and 2, symmetric
2	Load case 2- Slamming pressure in compartment 3, symmetric
3	Load case 3- Slamming pressure in compartment 4 and 5
4	Load case 4- Slamming pressure in compartment 6 and 7, symmetric
5	Load case 5- Slamming pressure in compartment 8 and 9, symmetric
6	Load case 6- Slamming pressure in compartment 10 and 11, symmetric
7	Load case 7- Slamming pressure in compartment 1 and 2 , axisymmetric
8	Load case 8- Slamming pressure in compartment 3, axisymmetric
9	Load case 9- Slamming pressure in compartment 4 and 5 , axisymmetric
10	Load case 10- Slamming pressure in compartment 6 and 7 , axisymmetric
11	Load case 11- Slamming pressure in compartment 8 and 9 , axisymmetric
12	Load case 12- Slamming pressure in compartment 10 and 11, axisymmetric

The ship structure was split into 56 sections. The

TABLE I

Bottom & Side Shell Pressure - Ps (kN/m2)										
Location on Bulkhead Above Baseline										
	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5
T	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
AP & 0	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
1	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
2	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
3	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
4	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
5	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
6	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
7	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
8	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
9	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
10	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
11	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
12	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
13	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
14	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
15	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
16	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
17	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
18	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
19	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
20	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
21	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
22	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
23	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
24	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
25	49.9625	46.2125	42.4625	38.7125	34.9625	31.2125	27.1	22.1	17.1	13.582
26	50.06044	46.31616	42.57188	38.8276	35.08331	31.33903	27.23059	22.26444	17.42681	14.02305
27	50.20922	46.47362	42.73802	39.00243	35.26683	31.53123	27.42896	22.51423	17.92322	14.69299
28	50.35799	46.63108	42.90417	39.17725	35.45034	31.72343	27.62732	22.76402	18.41964	15.36293
29	50.50677	46.78854	43.07031	39.35208	35.63386	31.91563	27.82569	23.0138	18.91605	16.03288
30	50.65554	46.946	43.23646	39.52691	35.81737	32.10783	28.02405	23.26359	19.41247	16.70282
31	50.80432	47.10346	43.4026	39.70174	36.00089	32.30003	28.22242	23.51337	19.90889	17.37277
32	50.95309	47.26092	43.56875	39.87657	36.1844	32.49223	28.42079	23.76316	20.4053	18.04271
33	51.10186	47.41838	43.73489	40.0514	36.36792	32.68443	28.61915	24.01295	20.90172	18.71266
34	51.25064	47.57584	43.90103	40.22623	36.55143	32.87663	28.81752	24.26273	21.39813	19.3826
35	51.39941	47.7333	44.06718	40.40106	36.73494	33.06883	29.01588	24.51252	21.89455	20.05254
36	51.54819	47.89076	44.23332	40.57589	36.91846	33.26103	29.21425	24.76231	22.39096	20.72249
37	51.69696	48.04821	44.39947	40.75072	37.10197	33.45323	29.41262	25.01209	22.88738	21.39243
38	51.84574	48.20567	44.56561	40.92555	37.28549	33.64543	29.61098	25.26188	23.38379	22.06238
39	51.99451	48.36313	44.73176	41.10038	37.469	33.83762	29.80935	25.51166	23.88021	22.73232
40	52.14328	48.52059	44.8979	41.27521	37.65252	34.02982	30.00771	25.76145	24.37663	23.40226
41	52.29206	48.67805	45.06405	41.45004	37.83603	34.22202	30.20608	26.01124	24.87304	24.07221
42	52.44083	48.83551	45.23019	41.62487	38.01955	34.41422	30.40444	26.26102	25.36946	24.74215
43	52.58961	48.99297	45.39633	41.7997	38.20306	34.60642	30.60281	26.51081	25.86587	25.4121
44	52.73838	49.15043	45.56248	41.97453	38.38657	34.79862	30.80118	26.7606	26.36229	26.08204
45	52.88716	49.30789	45.72862	42.14936	38.57009	34.99082	30.99954	27.01038	26.8587	26.75198
46	52.97865	49.40473	45.8308	42.25688	38.68295	35.10902	31.12154	27.164	27.164	27.164
47	52.97865	49.40473	45.8308	42.25688	38.68295	35.10902	31.12154	27.164	27.164	27.164
48	52.97865	49.40473	45.8308	42.25688	38.68295	35.10902	31.12154	27.164	27.164	27.164
49	52.97865	49.40473	45.8308	42.25688	38.68295	35.10902	31.12154	27.164	27.164	27.164
50	52.97865	49.40473	45.8308	42.25688	38.68295	35.10902	31.12154	27.164	27.164	27.164
FP	52.97865	49.40473	45.8308	42.25688	38.68295	35.10902	31.12154	27.164	27.164	27.164
51	52.97865	49.40473	45.8308	42.25688	38.68295	35.10902	31.12154	27.164	27.164	27.164
52	52.97865	49.40473	45.8308	42.25688	38.68295	35.10902	31.12154	27.164	27.164	27.164
53	52.97865	49.40473	45.8308	42.25688	38.68295	35.10902	31.12154	27.164	27.164	27.164
FE	52.97865	49.40473	45.8308	42.25688	38.68295	35.10902	31.12154	27.164	27.164	27.164

slamming load, wind load and water pressure loads were applied based on the values shown in Table 1,2 and 3.

B. Structure of the Vessel

For this study, characteristics of the vessel is having both aluminium grade 5083 alloy and steel, aluminium: density 2640 kg/m3, Modulus of Elasticity 7.1 x 1010 Pa, Poisson's coefficient of 0.33, for steel: density 7840 kg/m3, Modulus of Elasticity 20.6 x 1010 Pa, Poisson's coefficient of 0.3.

C. Finite Element Model

The vessel was modelled and discretized using computer aided design software, thus modelling the hull shapes and structural elements. This process allows to materialize the project to export it to the finite element analysis software. This

TABLE II

Fr. No	Main Deck - Load (kN/m²)					First Deck Above Main Deck - Load (kN/m²)				
	Open Deck			Sheltered Deck		Open Deck			Sheltered Deck	
	Z_d (m)	p (kN/m²)	p_d (kN/m²)	p (kN/m²)	p_d (kN/m²)	Z_d (m)	p (kN/m²)	p_d (kN/m²)	p (kN/m²)	p_d (kN/m²)
T	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
AP & 0	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
1	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
2	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
3	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
4	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
5	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
6	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
7	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
8	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
9	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
10	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
11	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
12	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
13	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
14	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
15	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
16	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
17	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
18	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
19	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
20	2.595	4.215	4.916	3.000	3.499	5.655	3.000	3.499		
21	2.595	4.215	4.924	3.000	3.505	5.655	3.000	3.505		
22	2.595	4.215	4.959	3.000	3.529	5.655	3.000	3.529		
23	2.595	4.215	4.993	3.000	3.554	5.655	3.000	3.554		
24	2.595	4.215	5.028	3.000	3.579	5.655	3.000	3.579		
25	2.595	4.215	5.063	3.000	3.603	5.655	3.000	3.603		
26	2.595	4.215	5.097	3.000	3.628	5.655	3.000	3.628		
27	2.595	4.215	5.132	3.000	3.653	5.655	3.000	3.653		
28	2.595	4.215	5.166	3.000	3.677	5.655	3.000	3.677		
29	2.595	4.215	5.201	3.000	3.702	5.655	3.000	3.702		
30	2.595	4.215	5.236	3.000	3.726	5.655	3.000	3.726		
31	2.595	4.215	5.270	3.000	3.751	5.655	3.000	3.751		
32	2.595	4.215	5.305	3.000	3.776	5.655	3.000	3.776		
33	2.595	4.215	5.339	3.000	3.800	5.655	3.000	3.800	1.300	1.647
34	2.595	4.215	5.374	3.000	3.825	5.655	3.000	3.825	1.300	1.657
35	2.595	4.215	5.409	3.000	3.850	5.655	3.000	3.850	1.300	1.668
36	2.595	4.215	5.443	3.000	3.874	5.655	3.000	3.874	1.300	1.679
37	2.595	4.215	5.478	3.000	3.899	5.655	3.000	3.899	1.300	1.689
38	2.595	4.215	5.512	3.000	3.923	5.655	3.000	3.923	1.300	1.700
39	2.595	4.215	5.547	3.000	3.948	5.655	3.000	3.948	1.300	1.711
40	2.595	4.215	5.582	3.000	3.973	5.655	3.000	3.973	1.300	1.721
41	2.595	4.215	5.616	3.000	3.997	5.655	3.000	3.997	1.300	1.732
42	2.595	4.215	5.651	3.000	4.022	5.655	3.000	4.022	1.300	1.743
43	2.595	4.215	5.685	3.000	4.046	5.655	3.000	4.046	1.300	1.753
44	2.595	4.215	5.720	3.000	4.071	5.655	3.000	4.071	1.300	1.764
45	2.595	4.215	5.755	3.000	4.096	5.655	3.000	4.096	1.300	1.775
46	2.595	4.215	5.789	3.000	4.120	5.655	3.000	4.120	1.300	1.785
47	2.595	4.215	5.824	3.000	4.145	5.655	3.000	4.145	1.300	1.796
48	2.595	4.215	5.858	3.000	4.170	5.655	3.000	4.170	1.300	1.807
49	2.595	4.215	5.893	3.000	4.194	5.655	3.000	4.194	1.300	1.818
50	2.595	4.215	5.928	3.000	4.219	5.655	3.000	4.219	1.300	1.828
FP	2.595	4.215	5.957	3.000	4.240	5.655	3.000	4.240	1.300	1.837
51	2.595	4.215	5.968	3.000	4.248	5.655	3.000	4.248	1.300	1.841
52	2.595	4.215	5.968	3.000	4.248	5.655	3.000	4.248	1.300	1.841
53	2.595	4.215	5.968	3.000	4.248	5.655	3.000	4.248	1.300	1.841
FE	2.595	4.215	5.968	3.000	4.248	5.655	3.000	4.248	1.300	1.841

Ref. [1] Tasneef "Classification of High-Speed Craft" published by Emirates Classification Society Effective from 1 Dec 2019

TABLE III

Slamming Pressures	
	psl (kN/m2)
T	62.313
AP & 0	63.440
1	65.943
2	68.447
3	70.950
4	73.453
5	75.957
6	78.460
7	80.963
8	83.467
9	85.970
10	93.445
11	96.089
12	97.087
13	97.998
14	98.820
15	99.554
16	100.200
17	100.758
18	101.228
19	101.609
20	101.903
21	102.108
22	102.573
23	102.964
24	103.282
25	104.821
26	104.974
27	104.415
28	103.857
29	101.751
30	99.645
31	97.539
32	90.356
33	87.280
34	84.586
35	84.586
36	84.586
37	84.586
38	84.586
39	84.586
40	84.586
41	82.695
42	78.523
43	74.350
44	70.178
45	66.006
46	61.833
47	57.661
48	53.489
49	49.317
50	45.144
FP	42.293
51	40.972
52	36.800
53	32.627
FE	31.376

allows for the analysis and observation of each of the members and their geometries so that they contribute to the structural rigidity and distribution of the loads applied to the vessel.

For the analysis of this structure, several factors were considered: First, the selection of element, which for the case study a Shell Quad 4 element was selected for having 8 nodes having 6 degrees of freedom and admitting normal loads to its plane, bending loads, membrane loads and moments. This is a tool that can analyse the slamming loads in the structure, and giving priority to rectangular and not triangular elements, since normal displacement in the elements can occur and cause nodes to not represent the physics of what is happening in the system, thus generating, possibly, error. Secondly, the aspect ratio of the elements, which should predominate in value close to 1 in symmetry and allows for evaluating the physical effects that occur in the time period. And thirdly, the quality of the elements. All this, allows for the generation of the appropriate mesh, resulting in better analysis results.

In the process of generating the mesh, the 1D beam elements for the supporting members were aligned to the 2D mesh, thus achieving a correct distribution of the elements, and allowing the analysis to be homogeneous with respect to the spatial distribution of the elements.

IV. Results

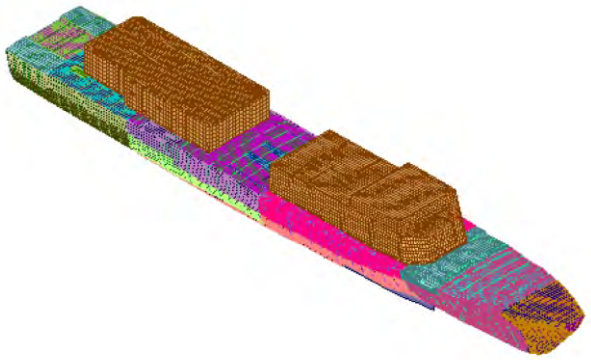

Fig.4. Meshed Model

Model meshed with 2D max quad plate elements

No of nodes	68448
No of elements	127405

Fig.5. Front View (Meshed Model)

The physical phenomena that occur in the vessel by the action of slamming load on the deck and hull, require a reliable result. It is necessary to evaluate the results of the stresses and deformation obtained and compare them with the acceptance criteria. The acceptance criteria are derived from the document Rules for the Classification of High-Speed Craft published by Emirates

Classification Society (Tasneef)
The peak stress obtained is 179.35MPa enveloped

C3.2.2.3 Material factor K for scantlings of structural members made of high strength steel

.1 The value of the material factor K to be introduced into formulae to check structures given in this Chapter and in the various Appendices is a function of the minimum yield stress R_{eH} value specified for the steel to be used.

.2 Table C3.2.1 shows the values of the material factor K to be taken depending on the R_{eH} value of the various high strength steels for hull structures for which $R_{eH} \leq 390$ N/mm².

Table C3.2.1

R_{eH} (N/mm²)	K
235	1,00
315	0,78
355	0,72
390	0,70

.3 The use of steels for which $R_{eH} > 355$ N/mm² will be considered in each separate case by the Society, which may stipulate special acceptance conditions.

.4 If, for special structures, the use of steels for which $R_{eH} < 235$ N/mm², has been accepted by the Society, the material factor is to be determined by:

$K = 235 / R_{eH}$

.5 In the case where the use of steels with R_{eH} values which are intermediate between those indicated in Table C3.2.1 is allowed, the values of the material factor K may be determined by means of linear interpolation.

Author: Rules of Classification of High-Speed Craft

across all the load combinations for Slamming, wind and external forces.

V. CONCLUSIONS

Fig.6. Von Mises Stress Envelope Results

Fig.7. Von Mises Stress Envelope Results Section View

The design and the results obtained, for the case study, comply with the criteria established by Tasneef. This, as a result of the application of the loads to which the vessel is submitted in its hull and the junction deck during the Slamming event, results in a structure that presents a maximum stress of 179.35 MPa, being 23% below the value characterized by Tasneef. In future work, and to ensure the structural integrity of the ship, the events of Splitting Moment, Tortional Moment and/or any combination of the above should be analysed. The process developed in this study, obtained adequate results to the parameters established by the Classification society by means of the use of FEM and the integration of different computer tools, making it a reference for the application of this in any type of vessel for further study in the Slamming event, because it has allowed to evaluate the designed structure by means of the obtaining of the stresses and deformations, characterizing those structural members under superior stresses by the loads of the system and their structural response. The use of computational tools for modelling, allows to analyse, from initial stages, to the designs of any type of vessel, obtaining, in respective, the possible failures of an engineering project, allowing for correction prior to construction of any structural optimization with the purpose of obtaining a functional design to satisfy the needs of the shipowner and the reduction of costs in a shipyard.

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Full scale fatigue testing of a fighter aircraft by Flight-by-flight methodology

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Abstract - The fatigue design of a fighter aircraft is a crucial aspect of its structural integrity and safety. Fighter aircraft are subjected to high-stress conditions due to the extreme manoeuvres, high speeds, and rapid changes in altitude they experience during flight. Fatigue design aims to ensure that the aircraft's structure can withstand these repetitive loads over its operational life without experiencing structural failures. The airframe designed with the above fact in consideration has to be demonstrated for full life clearance. It is an important milestone in from the certification point of view. The full-scale fatigue testing of the aircraft was carried out conventionally by block loading methodology. Although it simulates similar number of design load cycles, however, misses the actual damage what aircraft will experience when it undergoes variable amplitude cycles during manoeuvres.

A flight-by-flight full scale fatigue testing methodology is developed which not only simulates the design cycles but also simulate the variable amplitude and similar manoeuvre loads which the aircraft will experience in service during performance of any mission. This method gives a realistic fatigue damage accumulation and can be implemented on any typical fighter aircraft but not limited to it. The methodology also includes mplementation of flight-by-flight laoding for landing gear load cycle and other events like airbrake deployment, brake parachute deployment etc.

Keywords - Fatigue life, load spectrum, fatigue testing

I. INTRODUCTION

The structural design of an aircraft focuses on creating a robust and lightweight airframe that can withstand the stresses and loads experienced during flight. Engineers choose suitable materials and construction techniques to achieve strength while keeping weight to a minimum. Dilger et al [1] described about full aircraft fatigue testing (FSFT) of Eurofighter aircraft to qualify the airframe for full design life of 6000hrs. The scatter factor was assumed to be 3 [2] and as per that the required 18000 FH was simulated in blocks of 1000FH. The flights were formed using 700 different manoeuvres with an average of 4 load cases per manoeuvre.. Although the profile were formed using flight-by-flight approach however, the segments of the flight testing were not clearly defined as per the different mission requirements. FSFT of Su-22 aircraft were described by Leski et.al [3]. In this the testing was carried out in different phases. In the first phase, load spectrum contained the landing and taxiing were completed. The second phase of testing containing the flight loads of vertical g-force range of 0 to 6 were carried out with sub phases in terms of 'g' levels. This testing fails to capture the variable amplitude what occurs in a realistic flight. The testing was more or less similar to block loading fatigue testing kind.

This paper discusses preliminary about the fatigue design criteria for structure and later the full scale fatigue testing using flight-by-flight methodology. There are two main approaches to fatigue design - safe-life and damage tolerance. In the safe-life approach, the aircraft is designed with a predetermined fatigue life, and components are replaced at regular intervals before reaching the end of their life. In the damage-tolerance

approach, the aircraft is designed to withstand certain levels of damage without catastrophic failure, and inspections and repairs are performed regularly to detect and address any fatigue cracks or damage. This paper is based discusses mainly about the aircraft designed from Safe-life approach. The fatigue design of a fighter aircraft involves various aspects like load spectrum formation, material selection, Finite element analysis, fatigue testing, structural reinforcement, maintenance, inspection and certification. They are described in brief in following points.

A. Load Spectrum Determination

It starts with analyzing the expected flight profiles and missions the fighter aircraft will undertake during its lifetime. They determine the critical maneuvers, take-off, landing, and combat scenarios that will subject the aircraft to significant loads. This information is used to create a load spectrum with the help of Military Handbook (MIL-8866B) [3] , which represents the distribution of loads the aircraft will experience over time. The spectrum data available tuned for contemporary aircraft is also utilized as an input while formation of the final load spectrum. Leski et.al [4] has described about formation of load spectrum using flight data.

B. Material Selection

Choosing the appropriate materials for constructing the aircraft is essential. High-strength and lightweight materials, such as advanced composites and alloys, are commonly used to withstand the demanding operational conditions while minimizing the aircraft's weight.

C. Finite Element Analysis (FEA)

FEA is utilized to simulate the structural behavior of the aircraft under various loads and conditions. It helps to identify potential stress concentrations and areas prone to fatigue damage.

D. Fatigue Testing

Full-scale fatigue testing is performed on a prototype or a representative airframe structure of the aircraft to verify the predicted fatigue life. The aircraft structure is subjected to simulated flight loads and monitored for signs of fatigueinduced damage.

E. Structural Reinforcements

High-stress areas identified during analysis and testing may require additional structural reinforcements or design modifications to enhance fatigue resistance.

F. Maintenance and Inspections

A comprehensive maintenance and inspection program is essential to monitor the structural health of the aircraft throughout its service life continually. Regular inspections, non-destructive testing, and monitoring of flight hours are conducted to ensure any fatigue damage is detected and addressed promptly.

G. Certification

The aircraft must undergo rigorous certification processes, including fatigue testing and analysis, to meet regulatory and safety standards set by aviation authorities. It's important to note that the fatigue design process involves continuous improvements and updates based on real-world performance data and lessons learned from operating the aircraft. The goal is to ensure the fighter aircraft remains safe and reliable throughout its operational life while meeting the demanding requirements of modern combat scenarios. The full scale fatigue testing ensures the safety of aircraft structure during its service life. Thefore it is important to simulate the load spectrum as close as it is intended to be utilized in service. The flight-by-fligth loading method is developed to do this task. The detailed about the various testing and the developed methodology is described in following sections.

II. STRUCTURAL GROUND TESTING

Structural ground tests are essential for the design and qualification of an aircraft. These tests range from simple coupon tests which are used to collect basic material properties to the full scale fatigue tests (major airframe fatigue tests, MAFT) which is used to justify the required structural durability and where necessary the damage tolerance behaviour of the complete structure.

A. Material Data (Coupon Testing)

The materials that are going to be used for various components of the aircraft need to be tested for various properties which can be used extensively for design procedures. These tests include evaluation of material properties such as strength, stiffness and fatigue life etc.

B. Feature Testing

Various features that when added become components are tested and verified to be added to the sub-assembly for further testing. These include the shaped ribs, spars, landing gears internal wheel, etc.

C. Component Testing

Critical components are subjected to loads which is used in design of aircraft. The static and fatigue testing of the components are carried out. Static testing is done as as single cycle for its ultimate load. Fatigue testing involves cyclic loads till the limit load.

D. Full Aircraft Testing

This testing is done to test the full aircraft recreating its actual conditions to reveal even a small minute error that could happen. This too consists of static and fatigue testing. The full scale aircraft structure is tested to it's ultimate strength at room temperature (RT/AR) condition, which is referred as Main Airframe strength (MAST). The fatigue testing done here is for N- cycles (as found in fatigue spectrum safe life) and not one cycle. Hence also called Full-scale Fatigue testing.

III. PROPOSED FLIGHT-BY-FLIGHT METHODOLOGY FOR FSFT

The aircraft is designed for carrying various weapon configurations associated with different mission profiles involving different flight conditions. The flight conditions is also defined as points in the sky (PITS) which is a driving factor for the load experienced by the aircraft for different manoeuvre aircraft performs. Ideally aircraft should be tested for all the configurations and all the missions along with different PITS but practically that is not possible. It not only consumes lot of time but also very expensive to do the testing. Therefore,there is the need of rationalizing the parameters which affects the FSFT. The rationalization of three major parameters – Test configurations, Missions and PITS are explained below. The final objective after rationalization is to arrive at a test profile for ground testing of the full aircraft. A schematic of Flightby-flight test profile formation is shown in Fig 1.

A. Rationalization of Test configurations

It will be tedious task to test all the configurations in ground testing Therefore,it is required to rationalize the weapon configurations of the aircraft and arrive at rationalized and practical number of test configurations. The structural behaviour of airframe is manifested in the form of Bending moment and Torsion Moment of the full aircraft. This data is obtained for all the possible or cleared configuration for the aircraft. This data is handled separately for wing and fuselage. A typical bending moment plot along the fuselage axis is

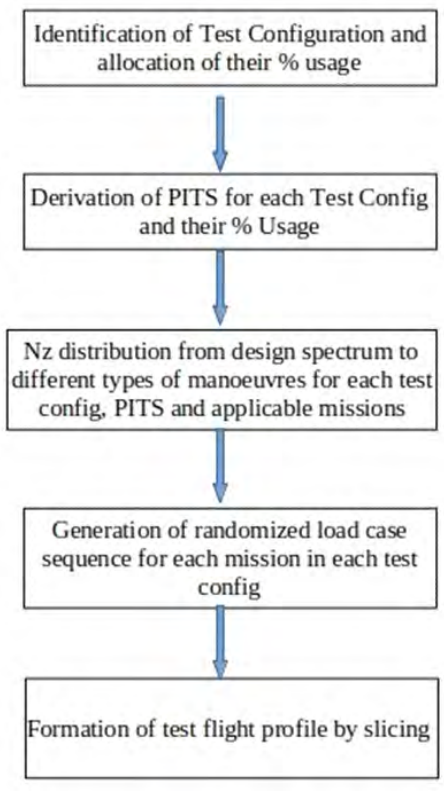

Fig. 1. Schematic for Flight-by-flight loading test profile formation for FSFT

shown in Figure 2 for different configurations. A correlation study is carried out between different weapon configurations which is shown in Fig 3. Those configurations which are closely correlated are merged. The correlation relationship is given as Equation 1.

B. Rationalization of Mission profiles

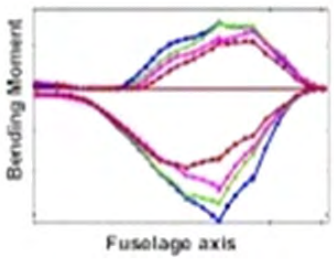

Fig. 2. Typical Bending moment about fuselage

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}}$$

Aircraft is designed to perform various missions majorly classified into Air to Air, Air to ground and miscellaneous missions. There are several sub-missions inside the major missions and testing for all again is not practically possible. Therefore, similarities between the missions in terms of manoeuvers and PITS are worked out along with the user. The similar missions are collated to form test missions

C. Rationalization of PITS

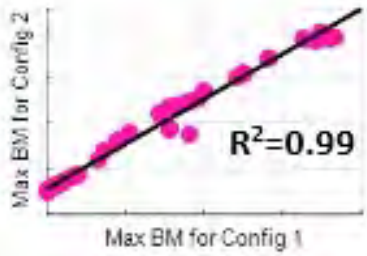

Fig. 3. Correlation of BM between two Configuration

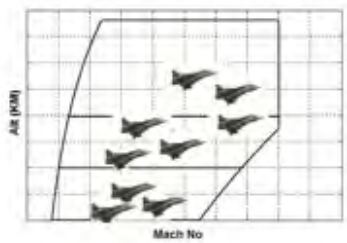

Fig. 4. PITS in terms of Mach-Alt envelope

The PITS are defined in terms of Mach No and Altitude in which the aircraft flies to perform the mission required manoeuvre. The loading on the aircraft is dictated by PITS, however there are infinite points in the envelope of Mach-Alt. Therefore, it is needed to rationalized based on similar CAS and percentage usage density. Generally, gradation of altitude would be the starting point in which different zones can be defined in terms of low, medium and high altitude. The PITS are shown in Fig 3.

D. Test profile formation

Once all the test case parameters are rationalized and we obtain a defined number of Test configurations, missions and PITS which are required to be tested. These parameters are utilized for formation of Nz, roll spectrums distribution among test configurations and missions. Further with PITS the gradation and distribution are made. A semi-randomized algorithm is utilized to distribute the Nz-roll data into various missions. The slicing is later on done based on how many flights are allocated for a particular mission. The full in-flight test profile is formed after appending Take-off and landing segments to the sliced profile. A typical test profile formed in this manner is as shown in Figure 4. All the formed test profile are later on validated back to the design spectrums. The architecture of the test profile generation for flight-byflight methodology is automated using MATLAB software.

E. Load applications

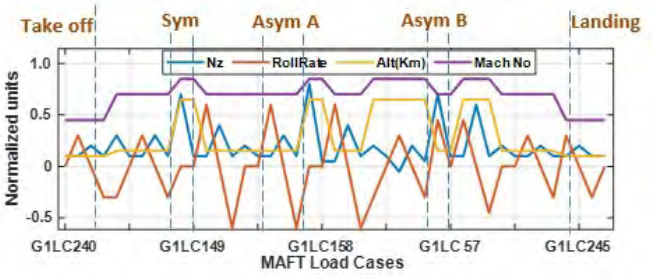

Fig. 5. Generated typical test profile

The loads for each test profile load cases are generated along and across the specimen. In this process, depending on the altitude the fuel and cabin pressurization is also captured. These loads

are applied on the full aircraft during simulation of Test profile.

IV. FSFT SPECIMEN AND LOADING SCHEME

The airframe structure is mounted on a test rig and for load application x number of actuators are attached as per the analysis as shown in Figure 6 [6]. It is to be noted that the aircraft should be balanced using reaction elements (actuators or rigid elements) in all the three Cartesian directions (x,y and z). It is a challenging task to balance the aircraft during application of distributed loading. The number of loading actuator required is decided based on the equivalence study of bending moment, shear force and torsion moment for critical load cases between FE analysis and ground test specimen. These loads are repeatedly applied by loading actuators according to the loading combinations and sequences for the duration of the aircraft's qualified life times the scatter factor. For each Test profile generated all the x no of actuator are assigned load as per the analysis and applied on the test specimen in a repeated way. The aircraft structure is inspected regularly and any cracks or damage monitored is fed back for redesign of the aircraft structure or amendments to the maintenance procedures.

V. CONCLUSION

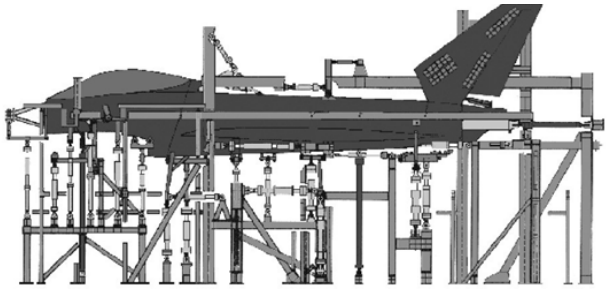

Fig. 6. Full scale fatigue testing setup of an aircraft [6]

A flight-by-flight methodology is utilized successfully for formation of test profile generation. It represents the respective design spectrum along with aircraft limits and envelopes in a realistic fashion. The realistic variable amplitude test profile for various missions replicate the usage as the aircraft will see in squadron. It has advantage over conventional block loading fatigue testing in terms of capturing the sequential effect of load cycles on cumulative fatigue usage.

The methodology presented here has made several rationalization to reduce the number of test cases, however it is not limited to the number of parameters. The reduction in the parameters through various rationalization lead to enormous saving in testing time eventually saves cost also. This method is deployed in MATLAB software and most of the steps are automated.

The test profile generated is validated back through various counting algorithms like level-cross counting, rain-flow counting etc [5] to the design spectrum. The results were found to be closely matching.

ACKNOWLEDGMENT

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A Control System design approach for Continuous Mixer and Extruder

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Abstract - A holistic design and development approach is proposed for process machine Control System of a Continuous Mixer and Extruder (CME). In this approach five frameworks are discussed to improve and standardize development cycle and machine life cycle.

Unlike traditional batch mixers, continuous mixer provides an economical alternation for big capacity mixing processes. CMTI has designed and developed a CME for a chemical processing research laboratory. The CME developed by CMTI is a fully automated system with all control operations automated for all process automation i.e., from silo to bin.

A top-down design approach is followed for control systems design. As recommended by ISA-88 norm, abstraction of equipment units allowed compartmentalization of operations. Further, abstraction enabled mapping operational requirements across life cycle from development to maintenance. The design is carried out considering all possible operations required throughout machine life cycle. This approach allowed for accelerated development, isolated unit testing, seamless integration and system testing.

A holistic approach in design and development of control system enables machine to be operated at variety of phases of development life cycle and machine life cycle. This is achieved with five major frameworks incorporated into the system.

The control system designed and developed consists both hardware and software. Software is developed into multiple Programmable Logic Controllers (PLCs). A network of multiple PLC systems and a central PLC that coordinates all control operations. This architecture forms a Distributed control system (DCS).

Keywords - Continuous Mixer and Extruder, control systems, development life cycle, process automation, DCS, PLC, frameworks.

I. INTRODUCTION

The CME is a twin screw mixer and extruder (TSME). The machine is developed for mixing various solid & liquid ingredients and finally extrude the extrudate (end product) through a die. It consists of multiple sub-systems like refilling systems, loading hoppers, solid feeders, liquid feeders, hydraulic power unit, lubrication unit, vacuum pump, screw driving motor, extrusion cutter, conveying and collecting system. Fig 1 shows systems and sub-systems arrangement of CME developed by CMTI.

The control system discussed in this paper, is designed and developed for the said CME. The control system for the CME is designed and developed with no prior suitable in-house expertise.

The CME requires running process steps parallelly unlike a batch mixer. The steps starting from material conveying, weighing, feeding, mixing, extrusion, cutting, conveying and collection are to be executed simultaneously. For operation life cycle of CME, the system shall have provisions such that all of the steps operated are either independently controlled or interlock controlled, depending on nature of operation like running the process or setting up the process.

The control logic/procedures that need to be executed are programmed into both central PLC as well as respective sub-system controllers. Control logic for process automation of the machine is programmed into 7 different controllers, some are industry standard PLCs and some are vendor specific controllers. This architecture forms a Distributed control system (DCS). The coordination of control is taken care by a central PLC.

The machine and control system for CME are designed to facilitate a chemical research lab with two aspects that are functionally at two different ends of requirements spectrum viz, 1) Experimentation platform for development of various recipes and recipe optimization 2) Fully automated machine with minimal operator interference for production.

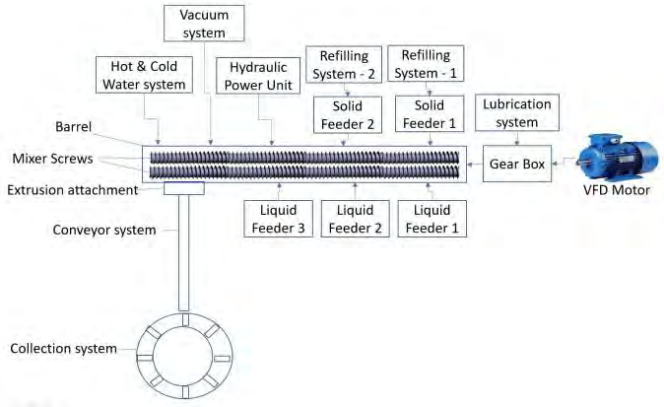

Figure 1: CME Machine and sub-systems

II. NEED AND SCOPE

The requirements with respect to machine and process are specified by the customer. However, strategies with respect to development life cycle are defined by design team in consultation with customer. Strategies for development are broadly adapted by design team, which are similar to any software development with goals such as modularity, maintainability, reusability and scalability. The development strategy is discussed in [1], that recommends analysing machine structure, designing interfaces between elements of machine and implementation.

The machine has variety of operational requirements like ease of maintenance, quick process setup, automated process execution, multiple user interfaces for independent operation and recipe access restrictions etc.

The CME machine needs to be designed with features like ease of updating machine safety limits, ease of updating process safety limits, ease of recipe development etc., which reduce modification overhead in case of any sub-system/device/ingredient replacement.

Apart from above requirements, due to first-time machine development following aspects are to be considered for machine realization to achieve synchronized cohesive progress. They are ease of integration/replacement of sub-system and ease of changing sub-system configuration settings.

Frameworks driven holistic approach in design and development of control system is considered to meet complexity in requirements and address uncertainties in development. Frameworks discussed in this paper enable machine control logic to be developed to meet above discussed requirements. Different sections of control logic developed are such that, they can be modified at various phases of machine life cycle. This is achieved with five major frameworks to be incorporated into the system that are a) Safety and Emergency b) Finite State Machine at the highest level of control logic c) Modes of operation and d) User authorization e) abstraction of equipment.

After adopting the said frameworks development time has reduced significantly. Development phases are documented and are guided by frameworks. Semantics of equipment and devices are dictated by frameworks and shared to every department involved in this prototype machine development process. The frameworks and their scope is shared with various teams like conceptual design, detail design, development, assembly and testing teams. This allowed respective teams to be prepared with their scope of contribution, and be ready with necessary interfaces for implementation.

III. DESIGN AND DEVELOPMENT OF FRAMEWORKS

The CME machine consists of multiple sub-systems like vacuum conveyors, loading hoppers, solid feeders, liquid feeders, hydraulic power unit, vacuum pump, screw driving motor, hot & cold-water circulation system, extrusion cutter, conveying and collecting system. During operation, all sub-systems have to communicate with central PLC in real-time for synchronous operation. Each sub-system can operate independently and has its own controller and stand-alone user interface. Apart from stand-alone user interface, CME machine is provided with centralized user interface with necessary SCADA functionalities in an Industrial PC.

To address the previously mentioned life cycle requirements, the control system includes five major frameworks that are

A. Safety and Emergency: hardwired relay logic.
B. Finite State Machine (FSM); designed to notify every sub-system in the machine present state of operation and control. This is a governing control logic for the entire DCS. The logic of overall machine FSM is executed in central PLC.
C. Modes of operation; that will enable necessary control options that otherwise are interlocked or disabled.
D. User authorization; three levels of operational authorizations are provided to demark operational access
E. Abstraction; of equipment as per ISA-88

A. Safety and Emergency

As mentioned earlier the machine has multiple sub-systems with their own control panels, controllers, actuators, sensors and user interfaces for independent operation. Hardwired relay logic is developed to identify and communicate emergency cases across panels. In this relay logic, all cabinets are connected to Master Control Relay (MCR), that can be triggered by any sensor or control panel in emergency relay logic chain. MCR in turn will signal sub-systems that there is an emergency.

The relay logic removes dependency on controllers availability and status of communication health. Part of relay logic is that, every sub-system control panel and user interface is provided with emergency push buttons. These panels and user interface stations are positioned across installation site for quick access.

Failure of any sub-system controller or smart device associated with sub-system or central PLC, is identified by central PLC by monitoring communication connection health and respective devices heart beat [4][5].

B. Finite State Machine (FSM)

FSM is a control logic designed to make sure that the system execution does not run into any indeterministic state at any given point of time.
FSM developed for this machine is a management control logic to handle and navigate emergency situations, machine boot up, equipment level control logic, machine/sub-system readiness, operator interface, process setup and process execution.

Figure 2 depicts a top-level state machine that represents CME machine state transitions and conditions. As there are multiple controllers in this DCS, machine state determined by the central PLC is communicated to sub-system controllers, so that sub-system controllers take necessary action. Once central PLC boots, machine enters emergency state, user has to manually turn master key for machine to exit emergency state and enter initialization state. Following, in initialization state readiness of the sub-system is learned by the FSM logic and other process essential interlocks listed as shown in figure 2. If these conditions are met, machine enters into ready for operation state, where the user is allowed to start process.

In fully automatic mode of operation if the user starts the process by starting screw motor, other feeders are also started automatically with set recipe feed rates, recipe process timings and sequence according to the selected library recipe. Once all bins are filled with products in collection system, it is identified as process completion. In

case of process completion machine notifies the user and goes to initialization state.

CME Machine state can enter to Emergency state from any state, this could be caused by trigger of a) sensors positioned in machine to identify emergency state b) sub-systems and their sensors identifying emergency case c) central PLC identifying any process value out of process limits or machine limits. C. Modes of operation

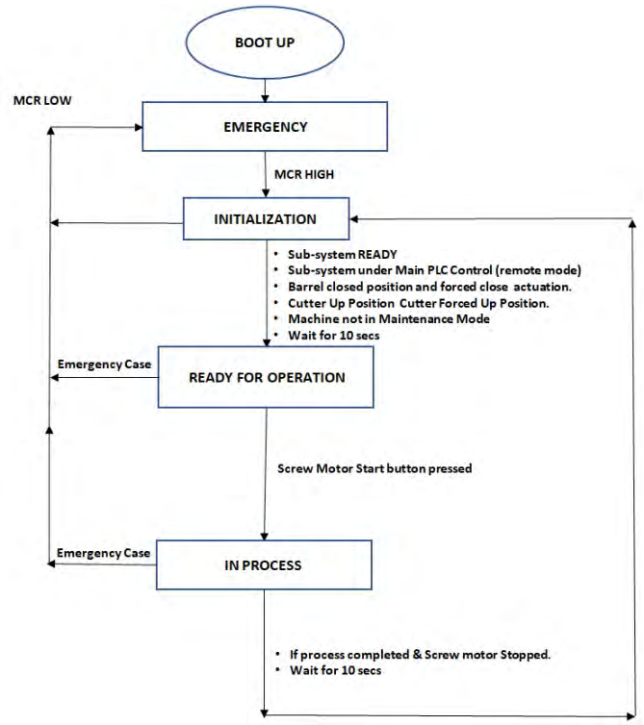

Figure 2: FSM of CME

C. Modes of operation

In this CME machine automation, three modes of operations exist, as discussed below

1. Fully automatic/recipe mode: In this mode of operation user selects a recipe from library and everything is taken care by central PLC control logic. User is enabled with minimal interface to start and stop the process, whereas, set points and process timings are defined in recipe. User cannot edit set points and process timings. In this mode control logic takes care of start, ramp, stop sequences of all feeders automatically as defined by library recipe. This mode can be selected by all users of authorization. The mode restricts individual operation of feeders. When this mode is selected at central user interface SCADA, operation is possible from the same central SCADA system, all sub-system user interfaces are disabled except emergency push button.
2. Individual unit operation mode: Individual unit can be operated w/o considering status interlocks from other units, this allows for independent operation of sub-systems either from main user interface or sub-systems user interface. In this mode necessary process & machine limits are considered as interlocks. This mode can be selected by users of authorization of either supervisor level or service engineer level.
3. Maintenance mode: In this mode individual actuators can be accessed; still necessary machine limits interlocks are considered. In this mode service engineer is enabled to access additional screens that allows him to edit main controller or sub-system configuration settings. Machine never enters 'In process state' or 'ready for operation' if it is set in maintenance mode. This mode can be selected only by a user of authorization of level of service engineer.

D. User authorization

The machine is provided with 3 levels of user authorization levels– operator, supervisor and service engineer

a. Operator can only operate the machine at fully automatic mode, where he can run an existing library recipe for production. Operator is restricted to access any recipe development fields on SCADA system.
b. Supervisor can operate machine in both fully automatic mode or individual unit mode to create recipes, set process limits and operate units individually for maintenance and calibration. Supervisor will be responsible for recipe creation, sequence feeders start & stop and process timings. A validated and proven recipe can be added to recipe library by the supervisor, for production by an operator.
c. Service Engineer can operate machine in all modes, he is also provided rights to change

machine limits. A service engineer is enabled to access additional screens that allows him to edit main controller or sub-system configuration settings.

E. Abstraction

The control logic handles various sub-systems, by following abstraction as per recommendations made in ISA-88 norm physical model as shown in below figure 3.

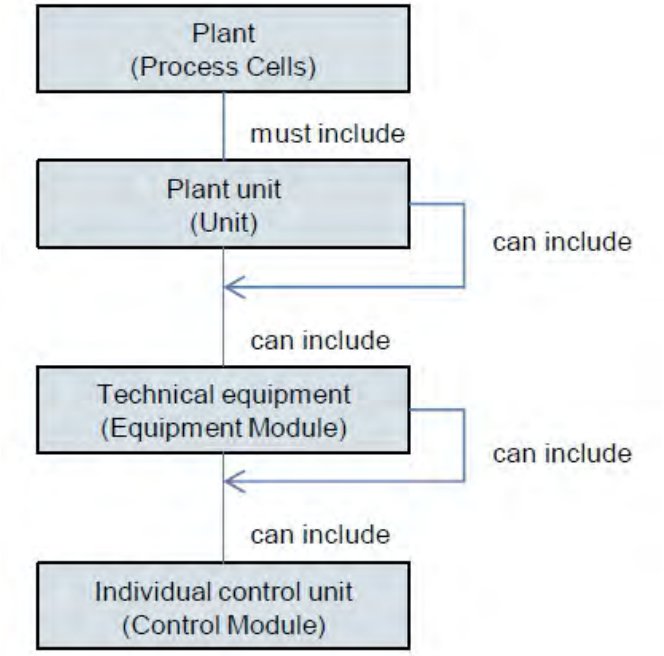

Figure 3: ISA-88 physical model

Every sub-system is dealt as a plant unit. For example solid feeder system is handled as a plant unit.

Solid feeder system has two feeders, each with their own control units. Each feeder is dealt as a technical equipment. So, one control logic is developed for one type of technical equipment, and is reused for other.

Liquid feeder system has 3 feeders, dealt as 3 technical equipment, but the control logic for them is developed once and reused thrice.

There are 9 plant units and 18 technical equipment in the CME.

Interlocks verification that needs to be carried out specific to individual technical equipment are handled in a separate function ('Feeder 1 logic control' as shown in figure 4), allowing its reusability. Interlocks verification to be carried out across technical equipment due to their dependency on readiness or operation status of other technical equipment are handled in separate function ('Input requests processing' as shown in figure 4).

Below figure 4 provides an overview of control logic function hierarchy designed for control of a solid feeder (individual technical equipment) separated for modularity and reusability.

From a solid feeder operation point of view, its control logic can receive start, stop and set rate requests either from a) Central PLC under Individual unit operation mode or from b) Central PLC under fully automatic operation mode. In case of individual unit operation, a set rate, start/ stop requests are provided in designated fields from centralized SCADA system. In case of fully automatic operation mode, these requests are from library recipe.

A feeder specific run request is processed based on a) application management logic functions b) Field entry in central PLC and c) state of other feeder/sub-system. This processing/verification is carried out at 'Input Requests processing' function of individual feeder logic (technical equipment level).

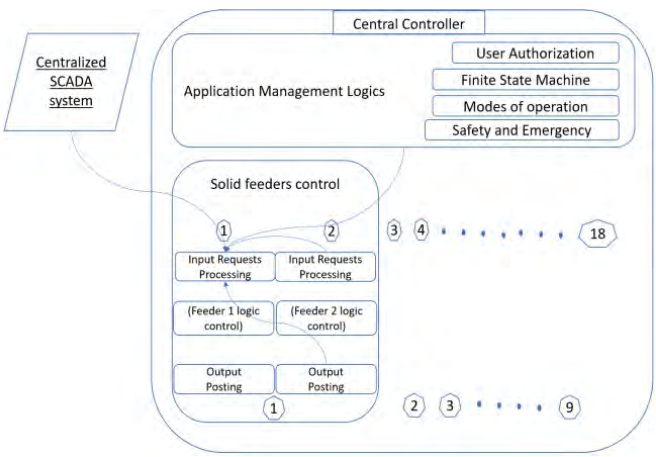

Figure 4: Control logic functions hierarchy

IV. RESULTS AND DISCUSSION

CME has various sub-systems which needs to be integrated to enable functionalities. During development life cycle of the control system of CME, every sub-system is available for integration to central system (PLC) at different point of times. Framework approach reduced dependency on availability of sub-systems. This is achieved due to well defined interfaces between application management logic and individual sub-system control logics. Interfaces definition here makes the automation solution modular, replaceable and scalable.

Any sub-system additions envisaged at a later point of time of development can be accommodated into the system, with minimum affect to existing automation.

Due to modeling of sub-systems as independent units, parallel control logic development by multiple engineers was possible. This resulted in reduction of development time significantly.

CME as mentioned earlier has multiple sub-systems. As and when sub-systems were available for integration, its respective central PLC control logic was developed for it. This development included realization of communication interface between the sub-system controller and central PLC.

FSM provides necessary diagnosis and trouble-shooting means, by which one can trace machine states transition history. During assembly of sub-systems to main system, any unwanted event is traced and triggers for the same can be identified. This provides crucial feedback for first time right development of CME machine and its automation.

V. SUMMARY

Frameworks discussed above greatly accelerated development and brought reliability to the development. These frameworks are made to be universal thanks to the abstraction that is masking underlying equipment unit functionalities. This allows them to be practiced across complicated process machinery control system.

Implementation of the recommendations allows to create rich library of equipment module control logics, signal processing logics that can be reused across projects. This accelerates development time as the adapted library module is already tested and qualified.

As the recommendations consider Control systems development life cycle, solution development time will be reduced, ready library/templates allow carrying out developments parallelly with multiple resources. As the library is already proven; adopting it to new developments deliver reliability and consistency.

When developing a novel control system solution, detailed specifications are not spelled out upfront, rather are identified during development process. Frameworks discussed, help in navigating last minute development of control requirements.

The framework covering variety of life cycle aspects for a complicated machine, like CME can be reused for any new prototype machine. As the engineers get familiar with components of the framework, this results in reduced development time, increased reliability and produce repeatable results in new prototype machine automation development operations.

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Investigation of Electric Field Distribution in Single Phase HV Cables Using Finite Element Modelling

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Abstract - Electrical wiring systems on aircraft have traditionally operated at low voltages (115V AC / 28V DC or in modern aircraft 230VAC, 270VDC). New emission targets require the commercial aerospace industry to develop hybrid and all electrical aircraft. Increased power will see the voltage level of the on-board electrical system climb to 0.75-3kV, the lower voltages being used for eVTOL air taxis, and the higher voltages (HV) being used in regional jet applications.

The higher network voltages generate the potential for partial discharge (PD) to take place between cables and within the cables themselves where voids exist. Partial discharges within an insulating material are usually initiated within gas-filled voids or gaps within the dielectric layers. Because the dielectric constant of the void is considerably less than the surrounding dielectric, the electric field across the void is significantly higher than that across an equivalent distance of dielectric. If the voltage stress across the void is increased above the corona inception voltage (CIV) for the gas within the void, PD activity will start within the void and breakdown of insulations materials will occur.

The objective of this study is to develop, PD free or PD resistant cables for future electric aircrafts by predicting the partial discharge inception voltage (PDIV) through electric field values obtained via simulation results. Here the simulations are carried out for single phase AC HV cables. The study has been conducted to understand the effect of insulation thickness, relative permittivity, gap between the high voltage conductor to ground and presence of shielding in electric field distributions in a prototype HV Cable. An empirical calculation methodology is established based on the dielectric breakdown testing results as well as Maxwell software simulation results to predict the PDIV in cables. By Implementing these simulation models and methodologies, it is estimated that, we have achieved approximately 20-30% reduction of the total project running cost which includes prototype building, production, people, and testing.

Keywords - Partial Discharge, High Voltage, Partial Discharge Inception Voltage, Electric field, Simulation, Cable, Dielectric

I. INTRODUCTION

For electrical components, the presence of partial discharge effects at operating voltage may result in a significant reduction of service life. In cables, some insulation materials are more susceptible to such discharge damage than others. Evidence of partial discharges occurring during operation are during as follows,

- The wire insulation thickness is insufficient for the applied voltage.
- Distance between contact cavities in connector is insufficient for the applied voltage.
- The quality of the insulation is inadequate possibly due to excessive size of internal cavities or voids.
- An overstress is present, resulting in a local reduction of the wire insulation properties.
- A leakage path is present, resulting in a local reduction of the connector insulation properties.

When an electric field is applied in a gas-filled region, no current flows, apart from capacitive current, unless there are free electric charges present. When the applied electric field strength is low, the current flow is usually related to external sources and is not sufficient to cause any PD. However, at higher applied electric field strengths, the free charged particles can gain energies from the field, resulting in ionization of the gaseous species by elastic or inelastic collisions. In gaseous environments and uniform fields, buildup of charge leads to an unstable situation, in which the current increases very rapidly while the applied voltage collapses. This usually results in a discharge bridging the electrode gap. However, in a highly non-uniform field, the charges can form a kind of electrostatic shield around the electrode where the electric field strength is greater and, therefore, causes quenching of the self-sustained discharge. Therefore, partial discharge and insulation breakdown are important specification requirements [2]. PDIV of a cable depends upon other parameters such as insulation thickness, quality of the insulating material, dielectric constant, medium of the cable surrounding, geometrical configuration of conductors and ground, gap between high voltage conductor to ground terminal, ambient conditions such as pressure, temperature, humidity etc. [3]. PD testing requires adequate laboratory facilities, and it is usually expensive due to the electrical source requirements, Number of prototypes building cost is also high as testing is destructive in nature. More often it's challenging to test in an extreme ambient condition such as low pressure, high temperature, and various gas mediums which all aircrafts experience at higher altitudes.

In this paper, a modeling approach and simulation methodology for predicting the PDIV in a single-phase AC high voltage cable is presented, through computing maximum electric field (Emax) and assessing the factors impacting these electric fields. Some of the available solutions used to predict the PDIV in cables are described.

I. METHODS AND RESULTS

A. Modeling and Simulation methodology

PD occurs along the entire length of a cable if the applied voltage is greater than the PDIV [1]. To develop a strategy for analyzing experimental data from a cable that also contains defects resulting in PD at specific locations, several assumptions need to be made. The model has been setup with the following assumptions,

- There are no defects in the conductor or any of the insulating materials.
- The overall conductor is made up of a central strand and all other strands are perfectly arranged around the central strand with equi-distance spacing between all strands.
- The cable is perfectly isolated, with no field effect from surrounding cables.
- All materials are perfectly isotropic and homogenous.
- Air is at Standard atmospheric temperature and pressure.

The electric field properties have been considered for four different cable designs, as shown in Figure 1. Each design uses a #00 AWG Conductor. The material properties of the layers are shown below in Table 1. The simulation boundary conditions are as below,

Solver: 2D Electrostatic

Excitation: Voltage (3kV), Ground (0V)

Boundary Condition: Dirichlet

Governing Equation: $\nabla 2v=0, E=-\nabla v$; Electrostatic Field Formulation

Output: Electric field (kV/mm)

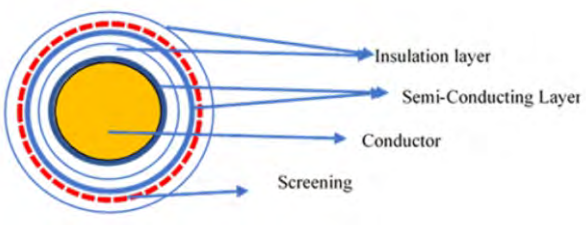


Figure 1:Typical configuration of prototype HV cable

Part	Name of Material	Conductivity (S/m)	Relative Permittivity(ε_r)
Conductor	Copper	5.8e7	1
Jacket/outer Insulation	PFA (Perfluoro Alkoxy)	-	1.6/2.3/2.8
Ambient	Air	-	1
Semiconductor Layer/Screening	PFA-Carbon black	25	10000

Table 1:Material and its electrical properties used in Simulation

B. Effect of Insulation thickness and Relative permittivity

One of the important parameters during the design development of the cable is the choice of thickness of insulation. Simulations have been conducted for various thickness of insulations and electric field distributions are plotted in the insulation as well in air surrounding, as shown below,

Case 1: Insulation thickness of 3mm, $\varepsilon r = 2.8$:

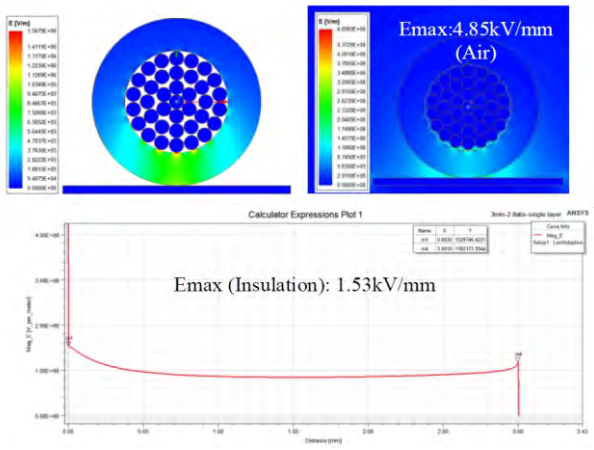
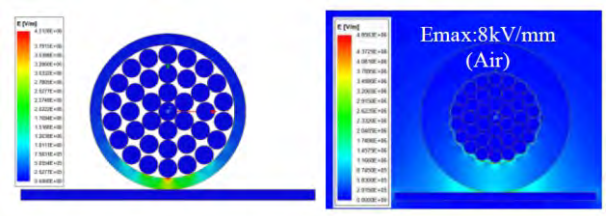


Figure 2:Electric field distribution in outer insulation, plotted across thickness of the insulation & plotted with air medium

Case 2: Insulation thickness of 0.8mm, $\varepsilon r = 2.8$



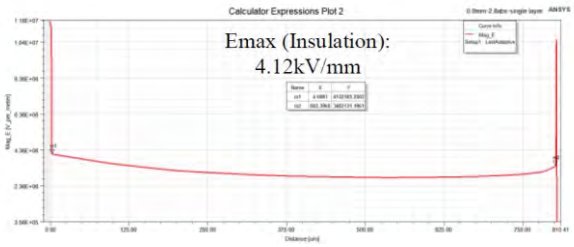


Figure 3:Electric field distribution in outer insulation, plotted across thickness of the insulation & plotted with air medium

Case3: Insulation thickness of 3mm, $\varepsilon r = 1.6$

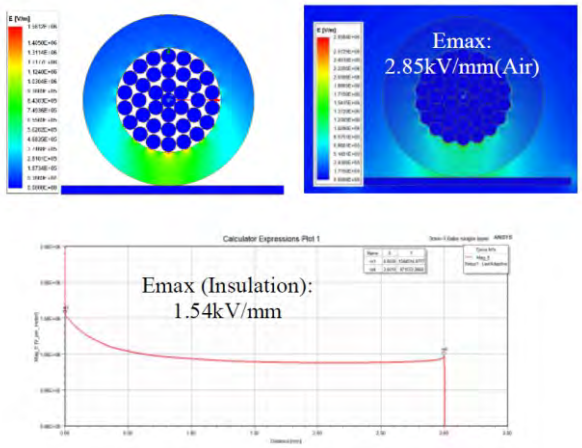


Figure 3:Electric field distribution in outer insulation, plotted across thickness of the insulation & plotted with air medium

Observations:

- By reducing the thickness of the outer insulation, the electric field in the solid and air increases
- Near the conductor region, in between the conductor and the insulation, the electric field is high
- By reducing the relative permittivity of the insulating material, the maximum electric field in the insulation increases whereas in the air medium reduces.

Solutions for the above problems are as follows,

Solution1:

Adding multiple layers in the outer insulation with optimum thickness and the layer closest to the ground should be of lowest permittivity and preferably close to the air permittivity.

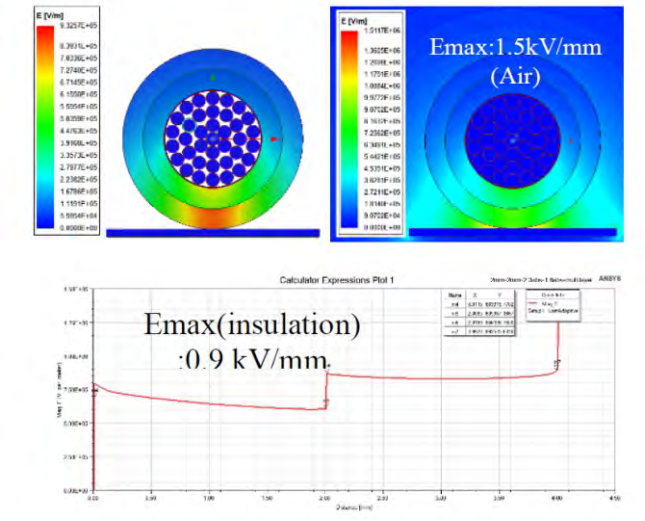


Figure 5:Electric field distribution in outer insulation, plotted across thickness of the insulation & plotted with air medium

Solution 2:

Adding semi-conducting layers (PFA-Black, εr=10000) above the high voltage conductor

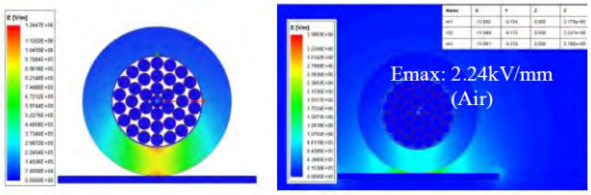


Figure 6:Electric field distribution in outer insulation & plotted with air medium with Semi-Conducting layer

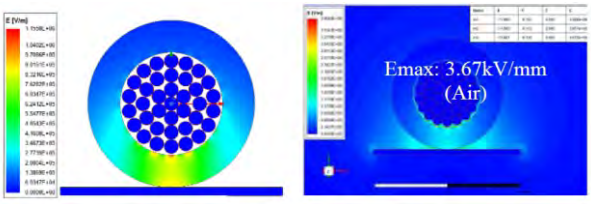


Figure 7:Electric field distribution in outer insulation& plotted with air medium without Semi-Conductive layer

The field electric lines exit or enter the conductor normal to the conductor surface. Because the conductor is stranded, the field strength can become very concentrated at certain points leading to local dielectric breakdown. A semi-conductor layer provides a smooth surface at the same potential as the conductor to keep the electric field consistent all the way around the surface. Without this layer, any small peaks or troughs could cause concentrations of electrical energy which could create small arcs, and over time could erode the insulation layer and cause failure of the cable. By adding a semi-conducting layer with a permittivity of 10000, the electric field near the conductor region is reduced by 40%.

Solution 3:

Adding Screening above the conductors

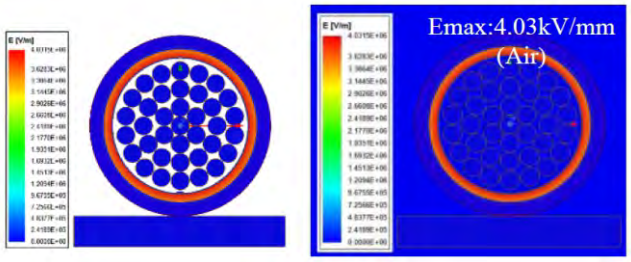


Figure 8:Electric field distribution in outer insulation & plotted with air medium with screening

The main function of the metallic screen is to nullify the electric field outside of the cable – it acts as a second electrode of the capacitor formed by the cable. The screen needs to connect to earth at least at one point along the route. The capacitive charging current and induced circulating currents which are generated under normal operating conditions will be drained away through the screen. The metallic shield needs to be electrically continuous over a cable length to adequately perform its functions of electrostatic protection, electromagnetic protection and protection from transients, such as lightning and surge or fault currents. By adding a screen as per the shielding effectiveness calculations, the electric field in the insulation layer gets more electric field as the screen terminals are grounded. Once the shield is grounded all the EMI related issues such as noise and surges will be bypassed to ground.

II. PDIV COMPUTATION FROM EMPIRICAL FORMULAE

By using all these observations, the PDIV directly from the simulation is challenging whereas using the test data an empirical approach can be made. To find the PDIV from simulation, the relation with t/ε with PDIV is given as PDIV is proportional the factor of t/εr.

Thickness of the insulation ti (μm)	ε_r	t/ε_r	PDIV (kV)
1500	2.6	576.92	3.24
3150	2.6	1211.54	5.65
2570	2.1	1223.81	5.38
3865	2.1	1840.48	7.81

Table 2:Tickness to Relative permittivity with PDIV from test data

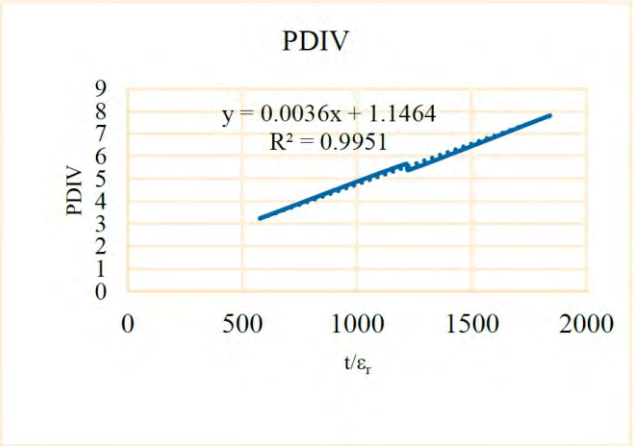


Figure 10: Curve fitted for PDIV with thickness to permittivity values.

K=8.00E+06(KV)		
PDIV-SIMULATION	PDIV-CURVE FIT	%ERROR
4.94	5.00	1.3
3.66	3.72	1.4
1.82	2.17	16.4
5.90	5.84	-0.9
4.41	4.28	-3.2
2.15	2.40	10.5
8.42	7.90	-6.6
6.30	5.65	-11.6
3.00	2.95	-1.9

Table 3:Comparison of PDIV with Simulation and Empirical formulae

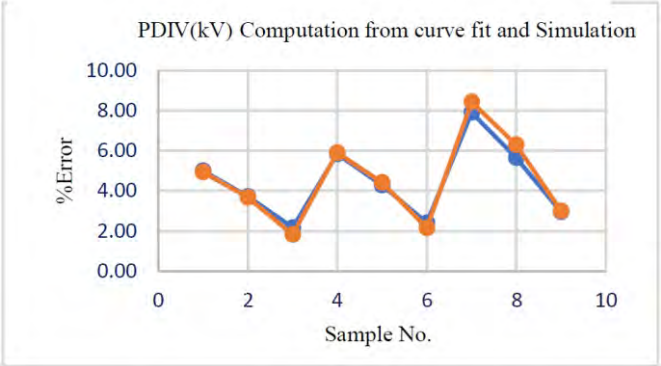


Figure 9:PDIV Comparison with Test data Curve fit and from Simulation data

III. DISCUSSION AND KEY POINTS

i. This approach is applicable only for the given single-phase configuration.
ii. This approach shall be used for other configurations with different empirical formulation.
iii. To capture the presence and levels of voids and impurities, more test data validations are required.
iv. Maxwell software can capture the electric field distribution across the insulator and in the surrounding air accurately, with change in voltage, thickness, dielectric constant, and gap size.
v. An extended study is required with Multiphysics solutions to understand the impact of extreme ambient conditions.
vi. Increased test sampling can improve the current prediction of PDIV.

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A Test Bed for Design & Evaluation of Multi Sensor Data Fusion (MSDF) Schemes

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Abstract - This paper elucidates the development of a testbed for integration/fusion of sensor observations from airborne targets obtained from sensors like Radar, Identification Friend or Foe (IFF), Electronic Support Measure (ESM), Automatic Dependent Surveillance-Broadcast (ADS-B), Automatic Identification System (AIS), Remote Tracks (RT), etc. under different scenarios. The testbed simulates and tests various state-of-the-art algorithms for target detection, tracking, association, fusion, identification, and threat assessment. Additionally, performance evaluation metrics for the comparison of various algorithms in complex scenarios are implemented. The testbed has the capability of post-execution performance analysis of new algorithms and comparative analysis with existing algorithms. The main use of this testbed is to test and benchmark the performance of various algorithms before deployment in the actual system and environment. Additionally, this paper discusses the challenges faced during the development and testing of the testbed.

Keywords - Multi Sensor Data Fusion (MSDF), Scenario Generator, Target Identification, Threat Assessment

I. INTRODUCTION

A modern battlefield scenario comprises of dynamically varying multiple threats. Multiple sensors are deployed to get better situation awareness that leads to a huge amount of data load on the operator, which in turn makes the decision-making more challenging. With the increase in the volume of data availability to an operator during any mission, there seems to be a real need for an automatic integration algorithm that can efficiently combine this high volume, real-time data from various collocated or dispersed sensors to arrive at a near-real-time picture of the operational field for better situational awareness.

Multi-Sensor Data Fusion (MSDF) is one such method that can achieve automatic detection, association, estimation, and fusion of the data/information received by various sensors/sources. It is a multidisciplinary area that uses concepts from various fields such as signal processing, information theory, estimation theory, artificial intelligence, etc. The main advantage of multi-sensor data fusion involves enhancements in the data authenticity and availability that help in improved detection, confidence, and reliability as well as reduction in data ambiguity. MSDF also helps in providing a unified view of the battlefield.

This paper elucidates the design and development of a testbed for multi-sensor data fusion of various airborne targets obtained from sensors in a simulated environment. This testbed enables to simulate large number of targets and responses of these targets to various sensors like Radar, IFF, ESM, ADS-B, AIS, and RT for different scenarios. Primary components of the testbed comprise real-time scenario generators, sensor models, algorithms, and integration architectures. The testbed simulates and tests various state-of-the-

art algorithms for target detection, tracking, association, fusion, identification, and threat assessment. Additionally, performance evaluation metrics for the comparison of various algorithms in complex scenarios have been implemented. The testbed has the capability of post-execution performance analysis of algorithms. The performance of newer algorithms can be benchmarked against existing state-of-the-art algorithms. The primary advantage of this testbed is to test and analyze the performance of various algorithms before deploying with actual sensor systems. Also, this paper discusses the challenges faced during the development and testing of the testbed. The proposed testbed also has the capability to test and analyze the recorded data of actual flight trials which helps for further fine-tuning of critical algorithm parameters according to the scenario.

The rest of the paper is organized as follows. Section II briefly describes the related works carried out in multisensory data fusion techniques, algorithms, and MSDF testbed. The MSDF architecture, algorithms, and performance metrics are described in section III. Sections IV & V discuss the use cases of the MSDF test bed, simulated results, and analysis of the proposed test bed. The conclusion of the proposed work is summarised in Section VI.

II. RELATED WORKS

In recent times, MSDF has been given more attention due to the increase in the vast application area of multiple sensor devices for various applications in both military and non-military applications for surveillance, detection identification, etc. A few of the related works are mentioned here. In [10], the authors have described the concept, analysis, and simulation environment for automatic target tracking and identification algorithm level simulation testbed. It provides a hardware/software platform to study the performance of various MSDF techniques for different applications. In [6], Lan et al have proposed an algorithm-level test bed for information fusion. Other information fusion-based work has been proposed in [7, 9]. There are various testbeds proposed that carry out data fusion for different applications [11,12,13].

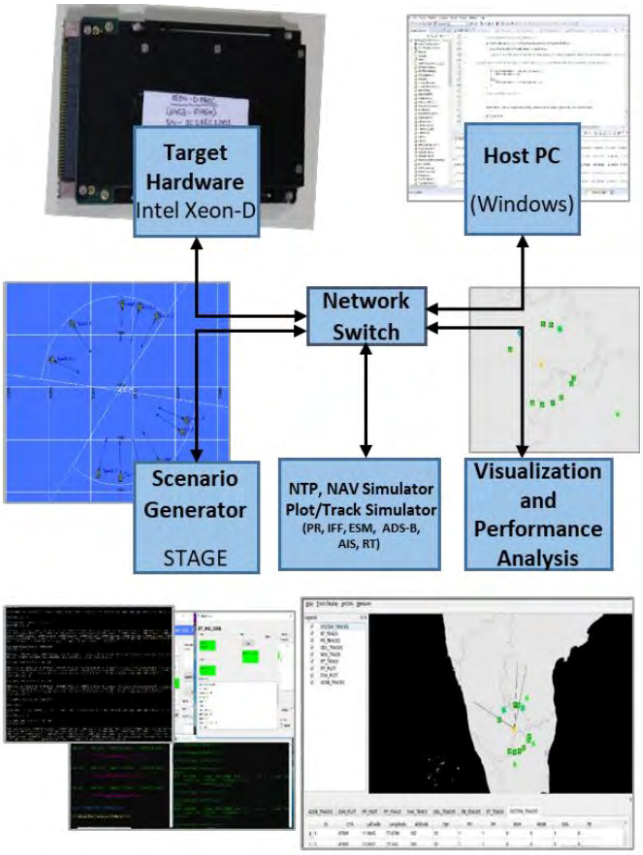


Figure 1. Framework of the proposed testbed

The existing MSDF testbeds have specific tasks to be carried out. They are designed to carry out application-specific tasks to fulfill certain objectives only. Sometimes, it is difficult to upgrade existing testbeds with new techniques as well as environments having complex scenarios. This paper designs and implements an algorithm-level test bed for airborne sensors and targets in complex environments.

III. PROPOSED METHODOLOGY

This section describes the proposed architecture, algorithms used in the proposed testbed, and performance analysis metrics.

A. Architecture

Figure 1 shows the basic architecture of the proposed MSDF test bed. It depicts the primary components of the test bed. It comprises of Scenario Generator (SG), various sensor simulators,

a Visualization and Performance Analysis system, and MSDF Target Hardware which are interconnected by a network switch. A scenario generator is used to build a tactical database and then simulate dynamic, interactive, complex, and real-time tactical and operational environments. These environments, called scenarios, contain individual platforms (such as fighter a/c, transport a/c, ships, etc) that interact through detection, communication, engagement and/or destruction. Various sensor simulators (like Radar, IFF, ESM, ADS-B, AIS, RT, etc) receives target information from SG and simulates detection of the targets based on the initialized parameters, that will be displayed in visualization system. In sensor simulator component, various configuration files will be loaded describing the sensor models, detection criteria, error models, miss models, etc. The sensor simulator generates the sensor data as per the loaded configuration files that will be further processed. Visualization and performance analysis system display the sensor data and processed results as per the scenario. The implemented MSDF algorithms are executed in the target hardware that is capable of processing large number of operations with least latency in real time. Host PC is used for developing and implementing MSDF algorithms for tracking, association, fusion, identification, threat assessment etc. All these testbed components are inter connected via network switch and share common time through Network Time Protocol (NTP).

B. Algorithms

Various state-of-the-art algorithms are developed, simulated, and implemented in multiple programming environments. There are various challenges arise due to imperfection in measurement data and due to the environment in which data are collected. Most of these challenges have been taken care during the development of the algorithms.

The algorithms of the test bed are grouped into sensor data preprocessing, association, tracking, fusion, identification, and threat assessment.

In the preprocessing stage, data alignments in terms of space and time are carried out. In space alignment, data is aligned to a common reference frame by coordinate transformation. The time alignment is carried out by interpolation and extrapolation methods.

In association, two types of association are carried out - plot to track and track to track association. Primarily used algorithms for the association are Nearest Neighbor (NN), and Global Nearest Neighbor (GNN) using various assignment methods like Munkres, Jonker-Volgenent-Castanon (JVC) [4], Probabilistic Neural Network (PNN) [2], etc.

In tracking the sensor observations, the Kalman Filter (KF) and its variants, the Extended Kalman Filter (EKF), and Interactive Multiple Model (IMM) Filters are used [1]. EKF is mainly used for angle-only tracking that is effective for ESM sensor data [14].

Once the sensor tracks are formed and associated, the fusion of the sensor tracks will be performed. Fusion is carried out using the associated state vectors and covariances obtained from the sensor tracks. The fusion algorithms/methods used are State Vector Fusion (Inverse Covariance Fusion), Kalman Filter, IMM Filter, etc. Other classical methods for association, tracking, and fusion are described in [1,3,5,8].

Additionally, the test bed performs Automatic Identification of the fused tracks/targets by fusing the available evidence sources. The considered evidence sources for automatic identification are flight plan association, IFF Mode Code association, ID area association, ESM identification, track kinematics, manual identification, etc.

The identification module is implemented using algorithms weighted voting logic and fuzzy logic. Other algorithms like Bayesian Networks, Neural Networks-based approaches, and Dempster Shafer Reasoning, could be utilized for Automatic Identification.

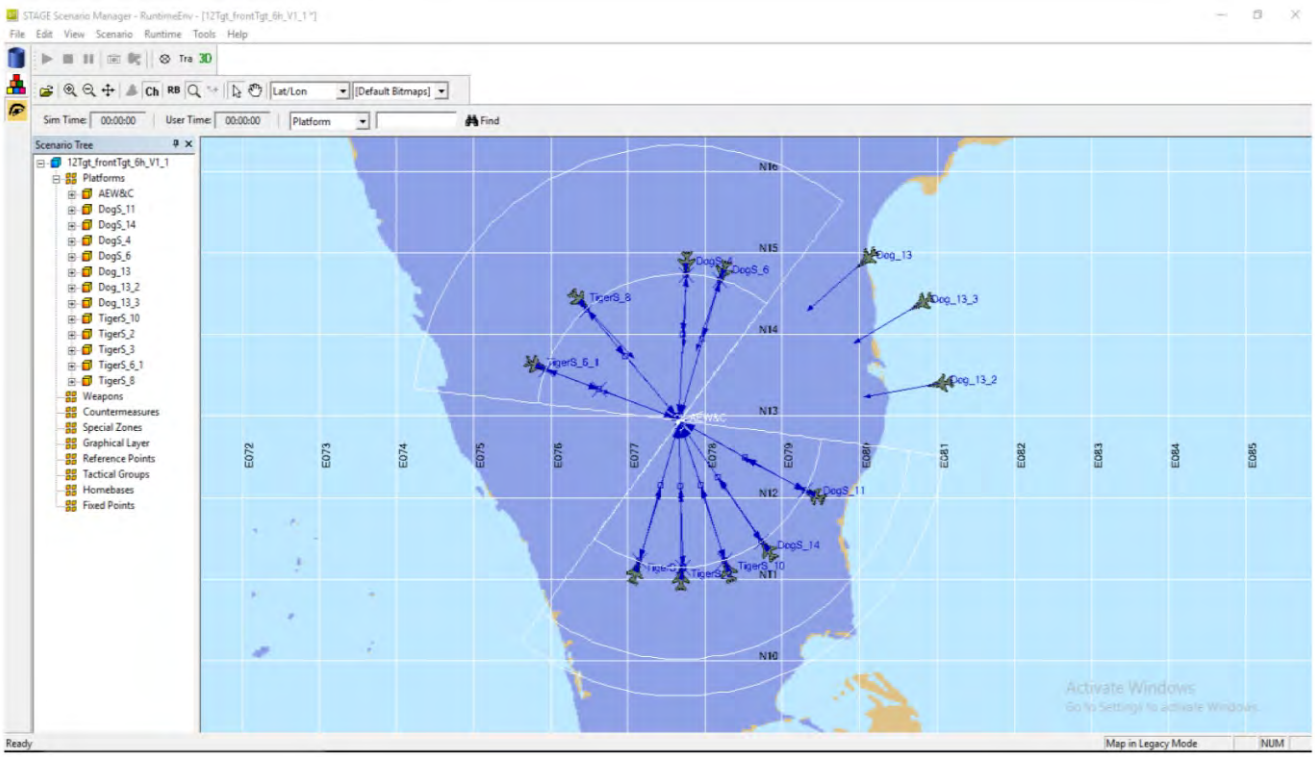


Figure 2. Snapshot Scenario Generator (SG)

Further, there is the provision of Automatic Threat Assessment that is capable of evaluating the threat from the detected and identified targets with respect to the assets such as fixed points/areas, and subsequently, alerts (approach, trespass) will be generated and displayed. The threat Assessment module is implemented using a rule-based fuzzy inference method.

C. Performance analysis metrices

The efficiency of the various MSDF algorithms is evaluated by the computation of certain performance metrics. The implemented metrics are Root Mean Square Error (RMSE), Track Purity, Track Switching Rate, Wasserstein Distance, Track Continuity, etc. RMSE is defined as the square root of the mean of the squared differences between actual and estimated values. Track Purity gives the percentage of correctly associated target detections in a track. This metric essentially measures what percent of a target's life was spent on its main track. Whereas track switching rate describes the number of events of a track changing its tracked object. Wasserstein Distance measures the distance between two probability distributions. Track continuity measures the number of tracks initialized on a given target. This metric measures the association algorithm's failure to associate data to an existing track.

IV. USE CASES

Various use cases depicting real-world scenarios have been created and tested to evaluate the performance of the MSDF testbed. By evaluation of the proposed testbed, the following cases are perceived.

i. MSDF testbed has the potential to integrate multiple sensors having different characteristics.
ii. It helps in extracting important sensor information from multiple sources with respect to time and space which is useful for ambiguity reduction.
iii. Helps for testing tracking, association, and fusion algorithms in complex test scenarios (like crossing over targets, manoeuvring targets, formation flying)
iv. Automatic identification and threat assessment under geo-political situations can be tested by creating tactical war scenarios.
v. Simulating more features of the targets

helps to achieve high confidence for automatic identification and threat level assessment.

vi. It has capabilities for load tests, memory tests, testing complex scenarios, etc.

vii. Performance assessment of various state-of-the-art MSDF algorithms can be achieved using a performance analysis tool.

V. RESULTS AND ANALYSIS

Figures 2-6 show the screenshots of the primary components of the testbed. Figure 2 shows a snapshot of the scenario generator that is used for creating complex scenarios of airborne and sea surface targets. The status of the sensor simulators is shown in Figure 3, where various sensor targets are simulated based on predefined sensor models and configuration files for different sensors. The sensor simulator application has capabilities of simulation of sensors like PR, IFF, ESM, ADS-B, AIS, etc. It also has the features of selecting the required sensors, defining sensor models, selection of sensor configuration files, recording of log files, etc. for specific test cases. It also shows the selected sensor outcome in the sensor detection data window depicted in Figure 3. Figure 4 shows the visualization of simulated sensor observations and the outcome of MSDF algorithms for one of the test scenarios that has features like displaying plot/track data, history, track kinematic parameters, association/fusion status, identification information, etc. Figures 5 & 6 shows the post-run performance analysis results. It has capabilities like comparing tracking, and association performance of different algorithms in the form of various performance metrics mentioned in section III. High-end computing systems are used for developing the testbed, which provides enhanced computational efficiency and real-time operational capability. The state-of-the-art algorithms are implemented using various software platforms/tools like Python, MATLAB, C/C++, QT, etc. that can be further upgraded as and when new algorithms are developed.

The main challenge in the testbed development is to standardize the interface for the selection of the algorithm that is going to be tested. The performance comparison of various algorithms

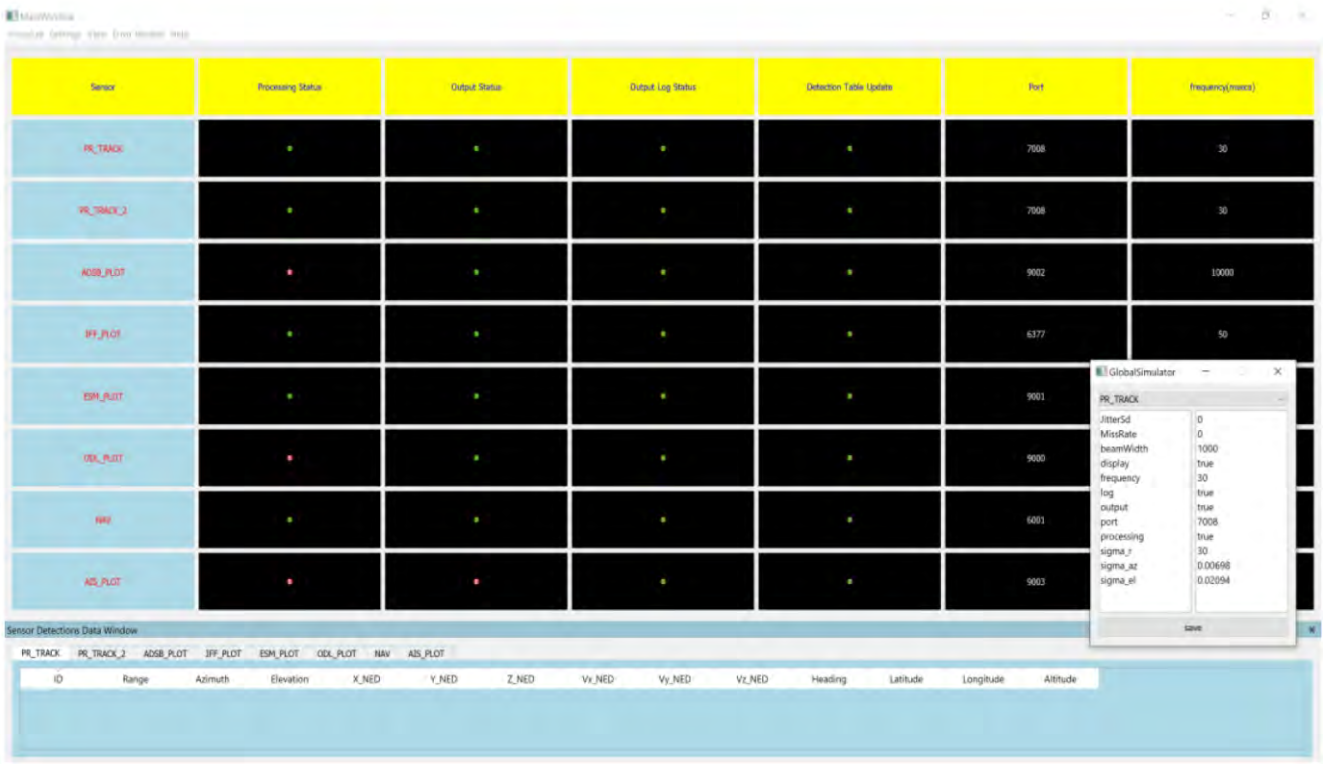


Figure 3. Snapshot of the status for Sensor Simulators (Green means sensor is 'ON', red means 'OFF')

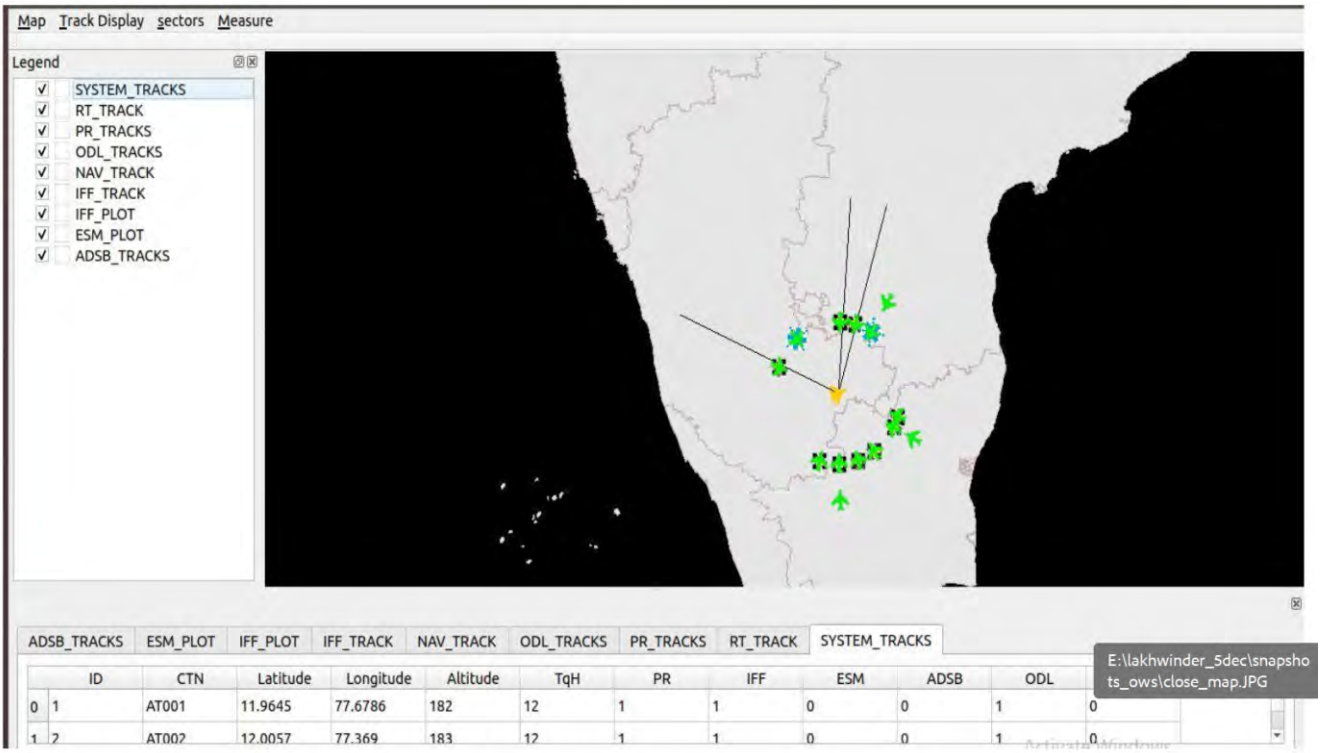


Figure 4. Snapshot of Visualization System

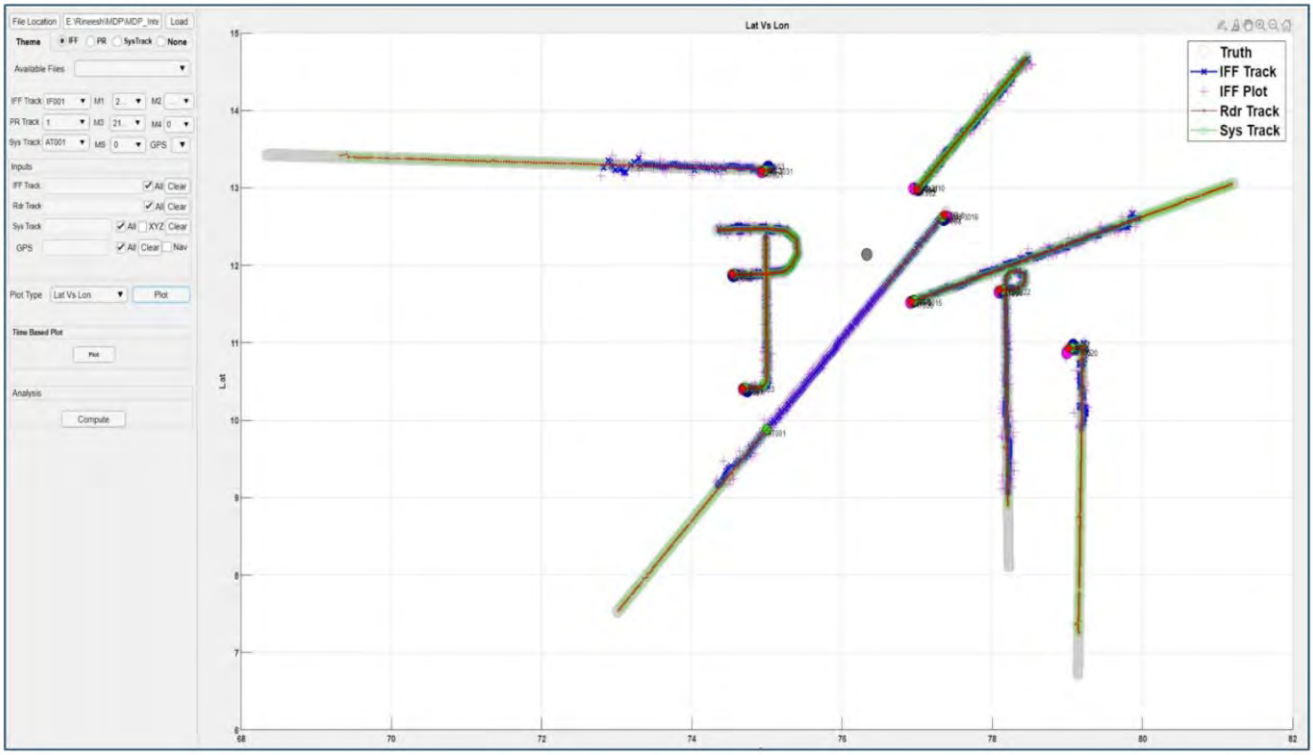
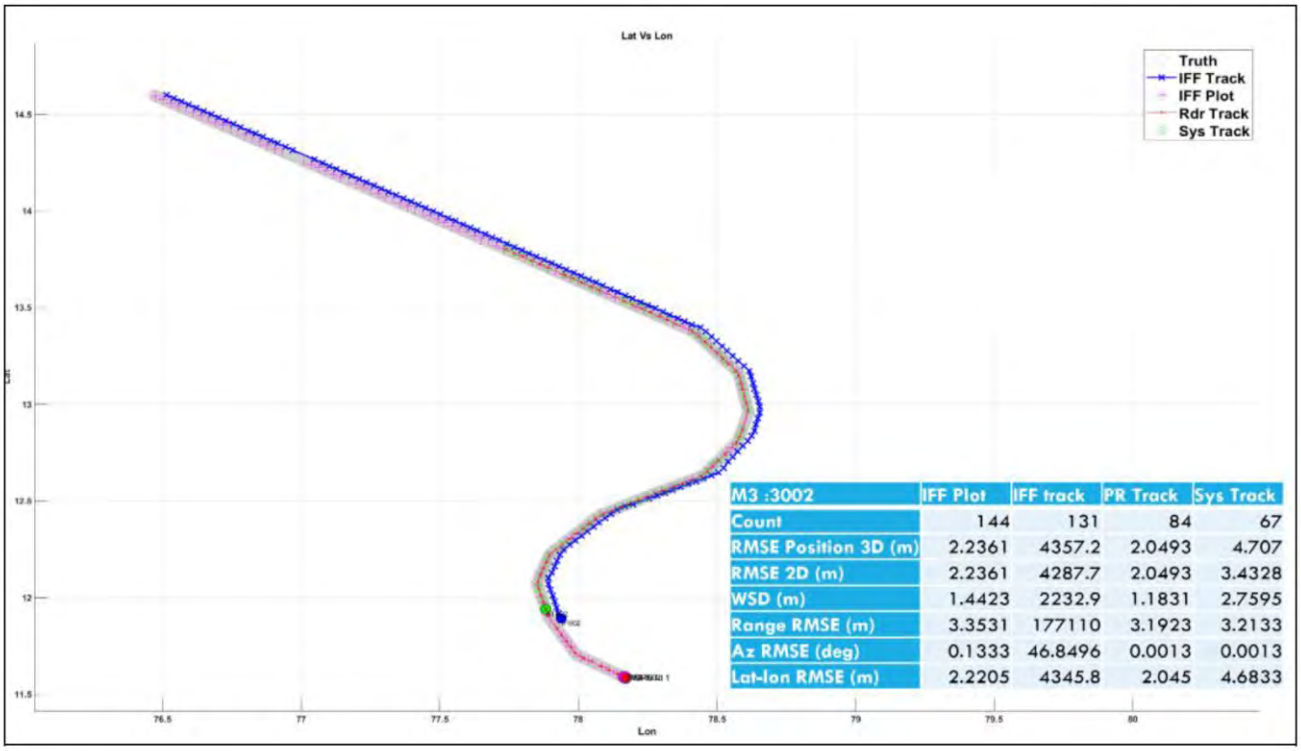


Figure 4. Snapshot of Visualization System



M3 :3002	IFF Plot	IFF track	PR Track	Sys Track
Count	144	131	84	67
RMSE Position 3D (m)	2.2361	4357.2	2.0493	4.707
RMSE 2D (m)	2.2361	4287.7	2.0493	3.4328
WSD (m)	1.4423	2232.9	1.1831	2.7595
Range RMSE (m)	3.3531	177110	3.1923	3.2133
Az RMSE (deg)	0.1333	46.8496	0.0013	0.0013
Lat-lon RMSE (m)	2.2205	4345.8	2.045	4.6833

Figure 4. Snapshot of Visualization System

mentioned in section III has been carried out. In target tracking problem, targets with dynamic motion characteristics are simulated. For tracking of such target different versions of Kalman Filter namely Interactive Multiple Models (IMM) and Constant Velocity Kalman Filter (CVKF) has been compared. It is observed that the IMM produces better performance in comparison to CVKF in most of the scenarios. In data association of ESM and radar in angle only coordinate, GNN-JVC algorithm is performing better in comparison to other association algorithms and it produces up to 95%, 90%, 80% accuracy for scenarios having faraway, nearby and crossing targets.

VI. CONCLUSION

This paper elucidates several designed and implemented state-of-the-art algorithms based on multi-sensor multi-target data fusion testbed in simulated environments using various programming languages like C, Python, MATLAB, using high-end computing systems. The testbed is robust, modular, and user-friendly. The performance analysis tool of the testbed is useful in analyzing the MSDF algorithms. Further, the tool can be used to analyze the recorded sortie data for any error correction and optimization of the algorithms. The future scope of the testbed will be to incorporate imaging sensors like EO/IR, and SAR for other airborne applications.

ACKNOWLEDGMENT

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Environmental Control System Flow Optimization for Fuel Tank Pressurization During Deck Take Off of Single Engine Jet Aircraft

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Abstract - In a military aircraft, most of the pneumatic & airconditioned demands are met through Environmental Control System (ECS). ECS conditioned air maintains cockpit and onboard electronic equipments within specified temperature range. ECS also supplies air for cockpit pressurisation, cockpit seal pressurisation, demisting, and Fuel Tank Pressurization (FTP). To meet ECS services, air is tapped from engine at 610°C (max) and 36 bar'g' (max). In case of naval single engine jet aircraft, it is required to maximize the engine thrust during deck take off. It is studied that almost 10% of engine thrust is lost for total 80 kg/min ECS bleed air. For deck take off period, avionics equipments are qualified to operate without force air cooling. Temperature of cockpit will be maintained within the acceptable limit for deck take off. However, FTP is mandatory requirement to avoid "Fuel Low Level" warning. Air flow of 1.5 kg/min for FTP and additionally 8 kg/min flow for heat exchanger ejector is tapped from engine. Ejector flow induces ram air inside heat exchanger to cool down FTP air. However, ejector flow is not required when aircraft rolling at Mach greater than 0.15. In this paper, two ECS states are discussed to meet FTP demand i.e. Engage state and Active state. In Engage state, FTP and heat exchanger ejector flow are tapped from engine. Active state is planned to operate for aircraft Mach greater than 0.15 to avoid additional bleed air of 8 kg/min. Active state is preferred to maximize the engine thrust during deck take off. Control logic of both Engage and Active states were built and tested on aircraft. During Engine Ground Run (EGR) test, Engage state was achieved successfully. However, ECS overpressure condition warning is posted during Active state. System 1-D simulations study is carried out to investigate overpressure warning and suitable proposal is made to overcome the warning.

I. INTRODUCTION

In most of military aircrafts, Environmental Control System (ECS) services are met from engine bleed air where bleed air is tapped from engine compressor. In Light Combat Aircraft (LCA), Engine bleed air is drawn from last stage of the compressor at 36 bar'g'(max.) and 610°C (max.) for ECS. The bleed air is routed through pressure regulating valve and various heat exchangers to bring down its pressure and temperature to meet ECS services. In a typical single engine military aircraft, ECS demands around 80 kg/min bleed flow and half of the bleed flow is fed to heat exchanger's ejector pumps to induce ram flow through the heat exchangers at low Mach and remaining ECS flow is utilised for ECS services. At high Mach, bleed flow for heat exchanger ejectors is not required as sufficient ram flow is available across the heat exchangers. Hence, bleed air is tapped to meet the ECS services only. In LCA, there are three ram air heat exchangers named as Precooler, Primary Heat Exchanger (PHE) and Secondary Heat Exchanger (SHE). The maximum Ejector flow of Precooler, PHE and SHE is approximately 10, 15 and 15 kg/min respectively. The amount of total ECS bleed air may change from aircraft to aircraft based upon ECS bleed conditions, architecture, and services. Typical ECS layout of single engine military aircraft is shown in Figure 1.

It is studied that there is approx. 10% engine thrust loss due to ECS bleed of 80 kg/min in LCA. In a single engine naval aircraft, there is a requirement to maximize thrust during deck- take off. It is

recommended to shut off ECS flow to its consumers for additional engine thrust. It is studied that nonavailability of cooling air to Cockpit and Avionics services is acceptable for Deck Take off period. However, FTP may be required during takeoff period to avoid "Fuel Low Level" warning. FTP flow requirement is only 1.5 kg/min but it needs heat exchanger ejector flow to cool down engine bleed air temperature from 610°C to FTP acceptable temperature limit i.e. less than 70°C. Hence, Flow to Precooler heat exchanger ejector alone is sufficient to cool down the bleed air for FTP. The engine thrust loss 2.5 % is estimated for bleed flow for precooler ejector and FTP flow during deck take off.

Two ECS schemes have been worked out named "Engage" & "Active" states for Deck Take Off operation. In Engage state, flow to all ECS consumers is closed except FTP & Precooler ejector as discussed above. However, In Active State flow to all ECS consumers is closed including Precooler ejector and FTP till Mach less than 0.15. It is studied through CFD that there is sufficient ram air flow inside Precooler, PHE & SHE to cool down 1.5 kg/min FTP flow when aircraft attains Mach ≥0.15. In Active state, only 1.5 kg/min of bleed air drawn after Mach ≥0.15. Deck take off point of view, more thrust is available in Active state compare Engage state. However, both Active State and Engage state control logics are built and configured in Naval version of LCA for flight testing. It is found during aircraft Engine Ground Run (EGR) that Active state posted overpressure warning in ECS. The overpressure phenomenon in Active state is simulated in AMEsim v2022.1 software.

II. Environmental Control System

A simplified ECS layout of single engine military aircraft is shown in Figure 1. The compressed air is tapped from engine and passes through Pressure Reducing and Shut Off Valve (PRSOV). The PRSOV reduces pressure of engine bleed air. PRSOV outlet air cooled in Precooler and PHE exchangers. After PHE outlet, ECS air is supplied to the Cold Air Unit (CAU) through an ECS Shut Off Valve (ECSSOV). In CAU, Compressor and Turbine are connected through a single shaft. ECS is first compressed inside compressor of CAU. The compressed air is cooled inside SHE. Moisture of ECS air removed using high pressure water separation system

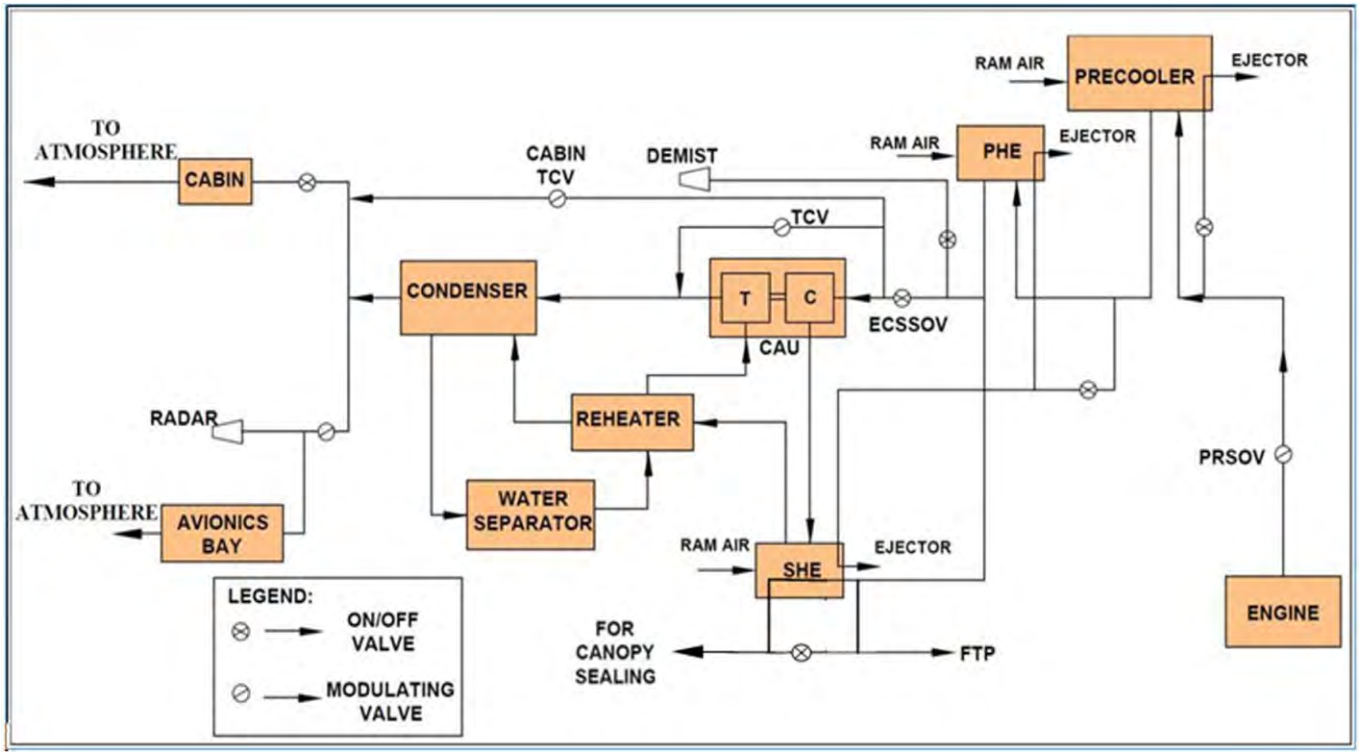

Figure 1: Environmental Control System of Single Engine Fighter Aircraft

which consist reheater, condenser and high pressure water separator. Almost dried ECS air enters the turbine side of the CAU. In the turbine, ECS air temperature reduces to subzero temperatures. The power generated by the turbine of CAU is utilized for driving the compressor of the CAU. Air leaving the turbine is heated to achieve predefined temperature at condenser (low pressure side) outlet. The condenser outlet air is further heated to attain cabin mean temperature set by Pilot. Hot air bypass lines mixes the hot air at turbine outlet and Cabin inlet as shown in figure 1. ECS Air for FTP and canopy sealing is tapped at the downstream of PHE and cooled inside SHE (if required).

III. Engine Ground Run (EGR) with Engage & Active states

EGR conducted to test ECS Engage and Active states exclusively. The purpose of EGRs is to check ECS transition from ECS Normal state (where flow is fed all ECS consumers) to Engage state (only flow to FTP & Precooler ejector). From Engage State to ECS transits to Active state (No Flow to any of ECS consumers till Mach ≥0.15). In the EGRs, several times transition to Engage and from Engage to Active states were tested as shown in Figure 2 & 3. PRSOV is kept open during EGR. Flow to ECS services is stopped by closing ECSSOV, precooler, PHE & SHE Heat Exchanger ejector valves, temperature control valves etc. It is not recommended to close PROSV for closure of all ECS services. The closure of PRSOV may lead to catastrophic situation incase fails to OPEN after deck take off due to non-availability of FTP.

EGR with Engage state

ECS is brought to Engage state from Normal state by not allowing flow to all the ECS consumers except Pre-cooler ejector and FTP valve. Ski state in Environment Control and Fuel Management controller (ECFM) bit transits from 2 (Normal state) to 3 (Engage state) when all the intended valves closed/opened successfully. ECFM is a controller for ECS & Fuel systems. The Ski states of ECS in EFCM is shown Table 1. In the EGRs, transition to Engage state is tested at IDLE, IRP and Max AB Power Lever Angle (PLA) conditions. ECS successfully transited and sustained in Engage state from Normal state at all PLA including maximum After Burner (AB). In Figure 4, transition to Engage state is expanded for bleed pressure at PRSOV outlet. PRSOV outlet pressure stabilizes at 6 bar'g' irrespective of increase in the engine bleed pressure.

IV. EGR with Active state

ECS is brought to Active state from Engage state by not allowing flow to any of ECS consumer including closing additional Precooler ejector and FTP valves. In first EGR, Ski state bit in ECS controller transits from 3 (Engage state) to 4 (Active state) and sustains for few seconds and then transits to 0 (Disengage state) due to overpressure at downstream of PRSOV. ECS overpressure warning is posted to Pilot for NO GO. ECS Controller transits to Disengage state for any of ECS failure and ECS can transits to disengage state from any of ECS states (Normal/Engage/Active). There are several builtin ECS failure logics in ECS controller which cause transition to Disengage state. In this case, ECS overpressure at PRSOV outlet let to ECS transition to Disengage state as shown in Figure 2.

Table 1 : SKI State of ECS

SKI State	Mode
0	Disengage
2	Normal
3	Engage
4	Active

It is observed that ECS transited Active state to Disengage state when PLA brought to IRP (Figure 3). Engine bleed pressure increase when PLA moved towards Max AB. ECS control posts overpressure warning when PRSOV downstream pressure builds is greater than or equal to 7.5 ± 0.35 bar 'g'. On ground, PRSOV normal regulation pressure is 6.35± 0.35 bar 'g'. It is analyzed that the overpressure condition is occurred due to engine bleed flow leaked through PRSOV. The leaked flow is kept on increases the PRSOV downstream

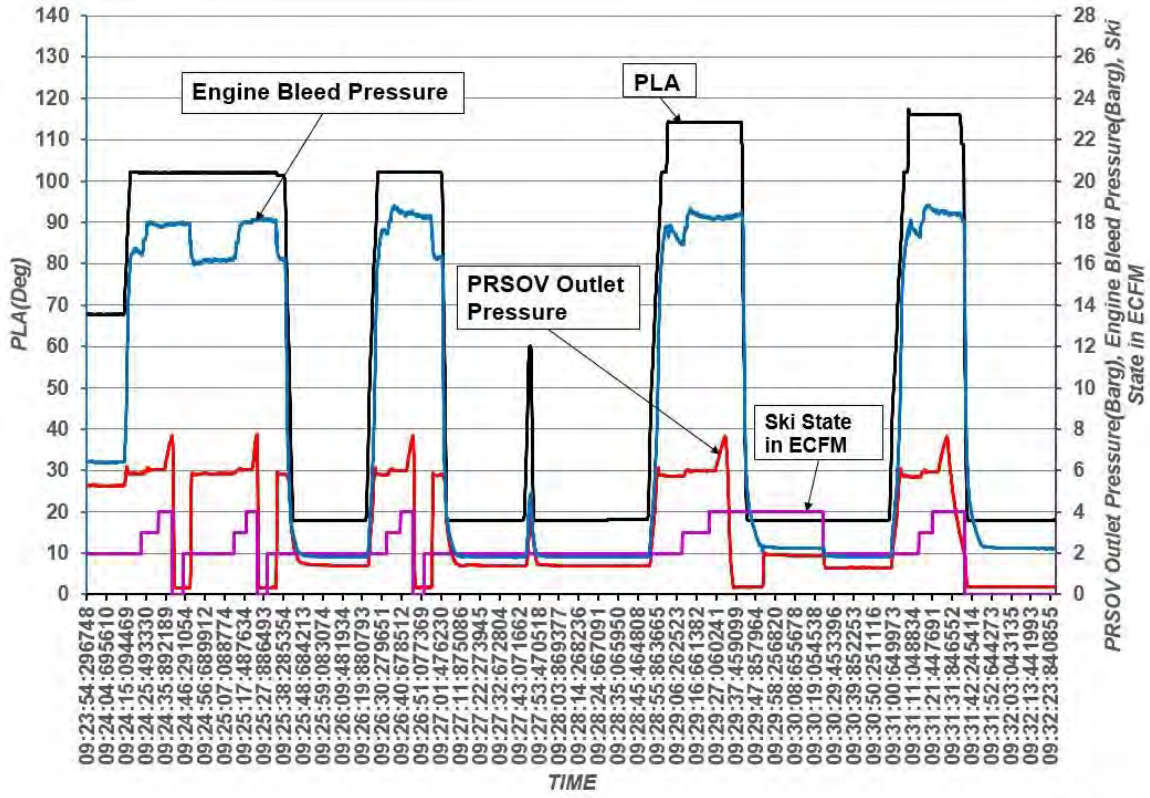

Figure 2: First EGR to test Engage and Active state

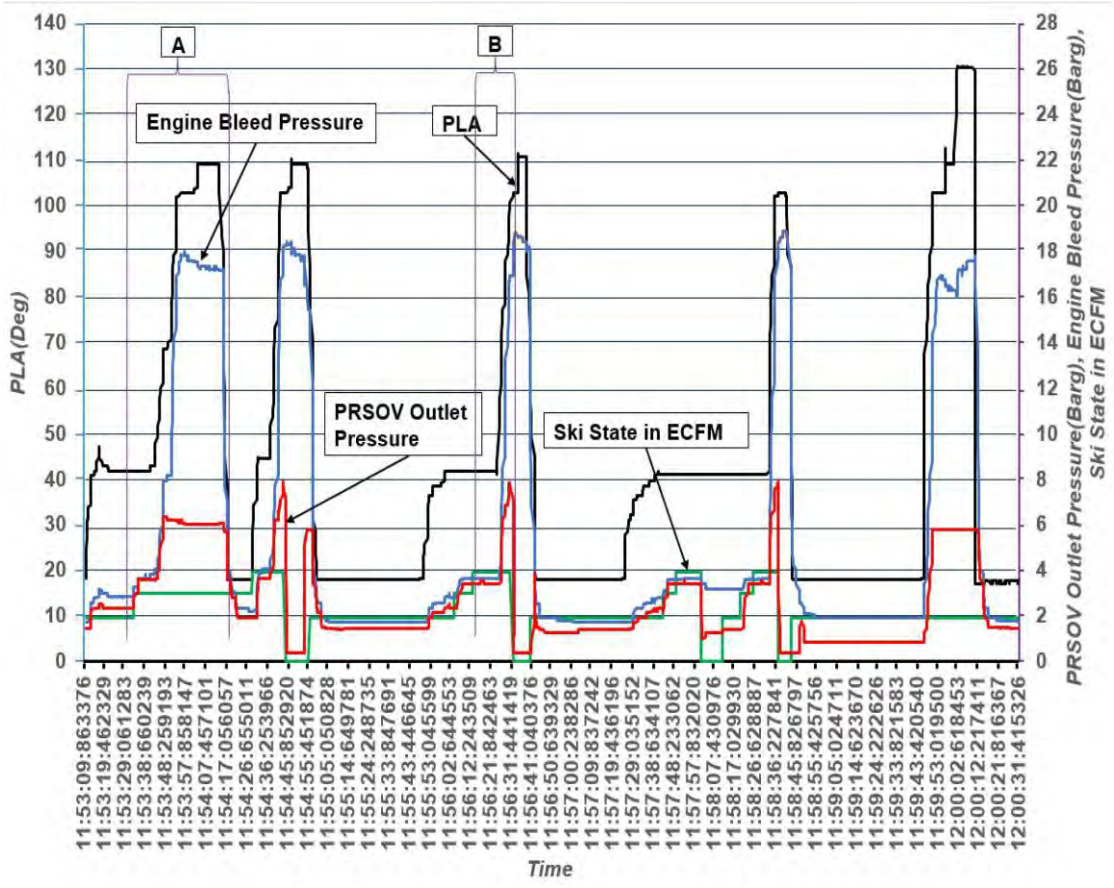

Figure 3: Second EGR to test Engage and Active state

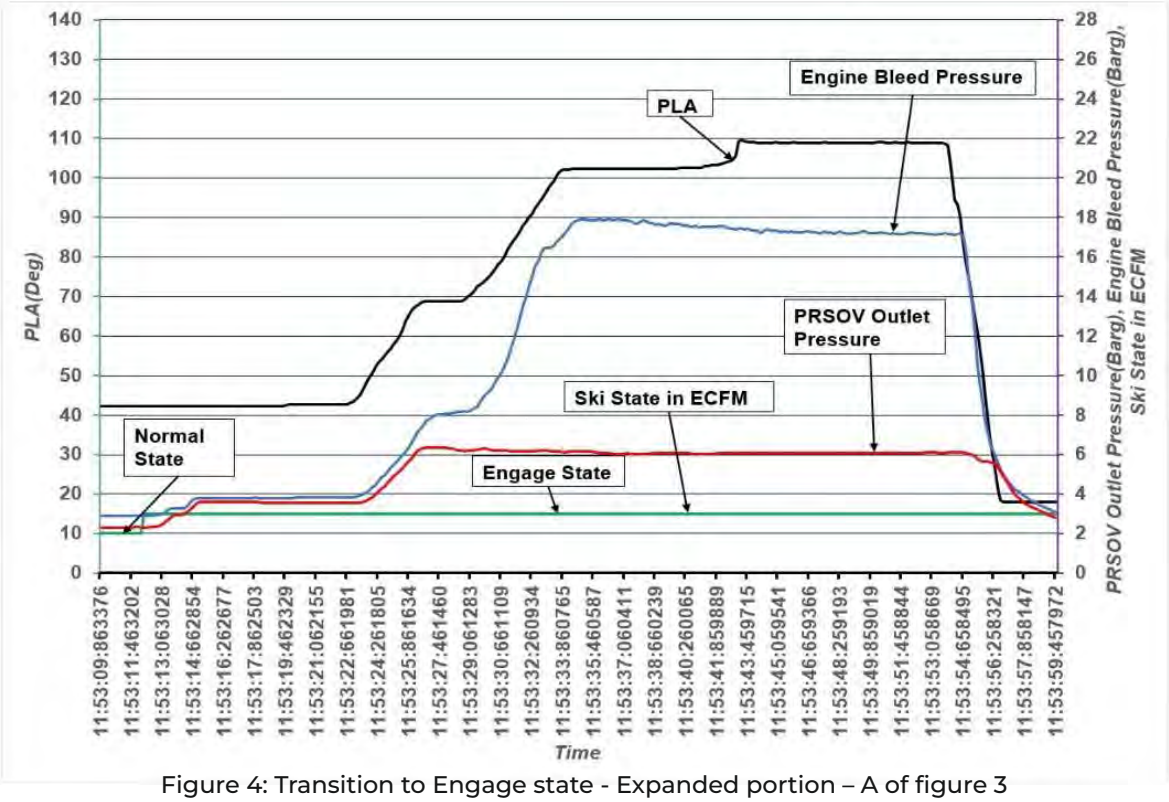

Figure 4: Transition to Engage state - Expanded portion – A of figure 3

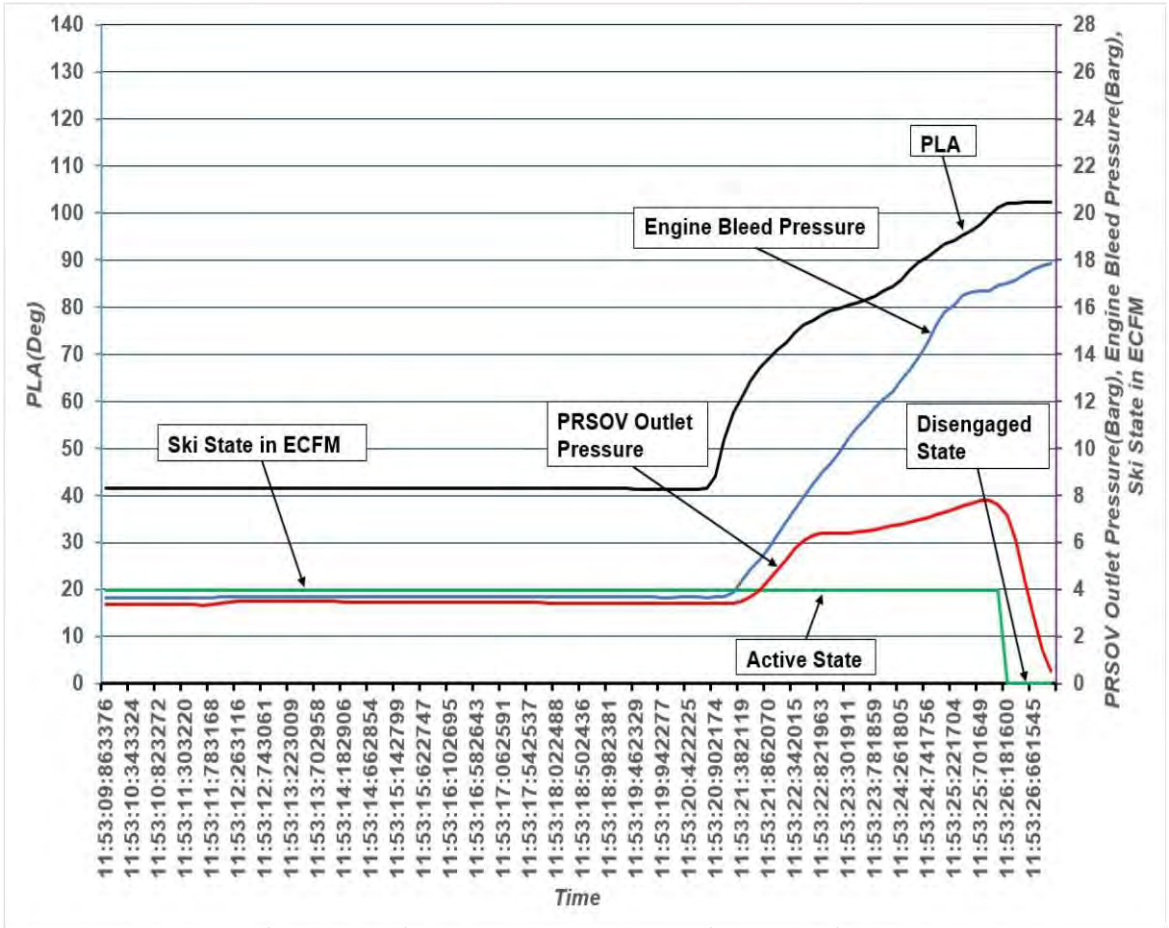

Figure 5: Active state - Expanded portion – B of figure 3

pressure till over pressure condition limit triggered. Due to overpressure condition ECS transits to Disengage state. The engine bleed air pressure to ECS system increase as PLA increases. When PLA moved to IRP, PRSOV outlet pressure is reached to overpressure condition set value. In Active state, all the downstream ECS services are closed by closing the respective consumer valve. The engine bleed flow leaked through PRSOV is trapped at PRSOV outlet and the leaked flow pressure reached to overpressure condition set value when PLA at IRP.

In Engage state, overpressure condition is avoided since Precooler ejector valve is kept open which relieves the excess pressure.

In Figure 5, Active state is expanded to investigate increase PRSOV overpressure condition. PRSOV outlet pressure increases almost at constant rate till its regulation pressure i.e. 6.35 bar 'g'(on Ground). Further, PRSOV outlet pressure increases slowly with increase in Engine bleed pressure. It is investigated that increase in pressure after PRSOV regulation limit is due to small quantity of bleed air leaked through PRSOV into ECS system. This leaked air through PRSOV is trapped at the outlet of PRSOV due to closure of all the downstream valves in Active state. PRSOV outlet pressure hits the overpressure limit. As design safety feature, once overpressure limit is reached, heat exchanger ejector valves opened and PROSV is closed to bring down the system pressure immediately.

System simulation of ECS architecture:

ECS architecture till ECSSOV is simulated on AMEsim V2022.1 software as shown in Figure 6. There is no flow at the downstream of ECSSOV for Engage & Active State. The purpose of the simulation is to capture the overpressure condition and to arrive at the suitable solution to avoid overpressure condition.

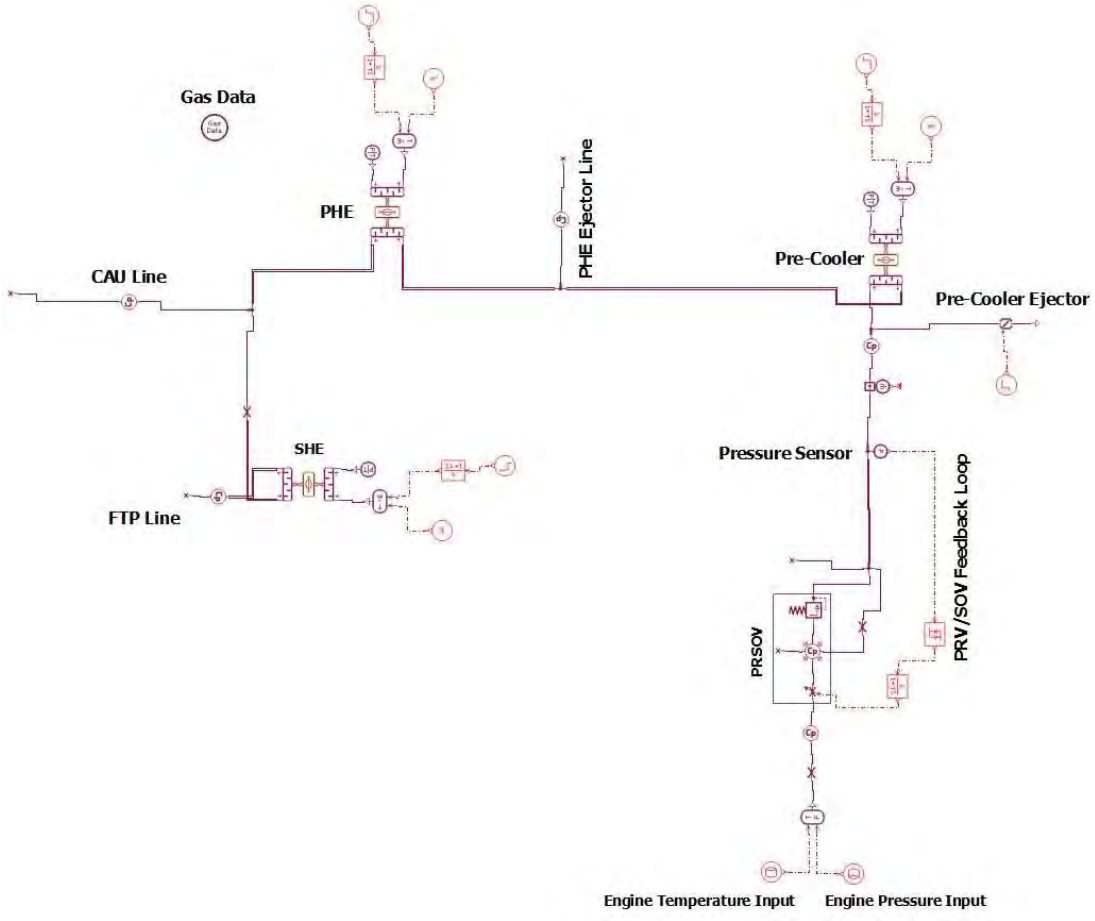

Figure 6: ECS system simulation architecture on AMEsim platform

V. Validation

ECS simulation is validated through flight data. In Engage & Active states, PRSOV outlet pressure sensor data is plotted with simulated PRSOV outlet pressure data as shown in Figure 7 & 8. PRSOV outlet pressure closely matches with the simulated value.

VI. ECS simulation with Relief valve

There is requirement to relieve the excess pressure/ leaked flow from engine bleed air through PRSOV during Active State. A relief valve is tried at the outlet of the PRSOV in ECS simulation model as shown in Figure 9. Relief valve meant to relieve excess pressure during engage state. The simulation study is performed to establish suitable crack opening pressure of relief valve to avoid overpressure condition at the downstream of PRSOV. It is required that the crack opening pressure shall be in between of 6.7 bar'g' (PRSOV normal regulation pressure higher tolerance limit) to 7.15 bar'g' (Overpressure condition lower tolerance limit) to avoid interference with PRSOV normal operating pressure and bleed overpressure condition.

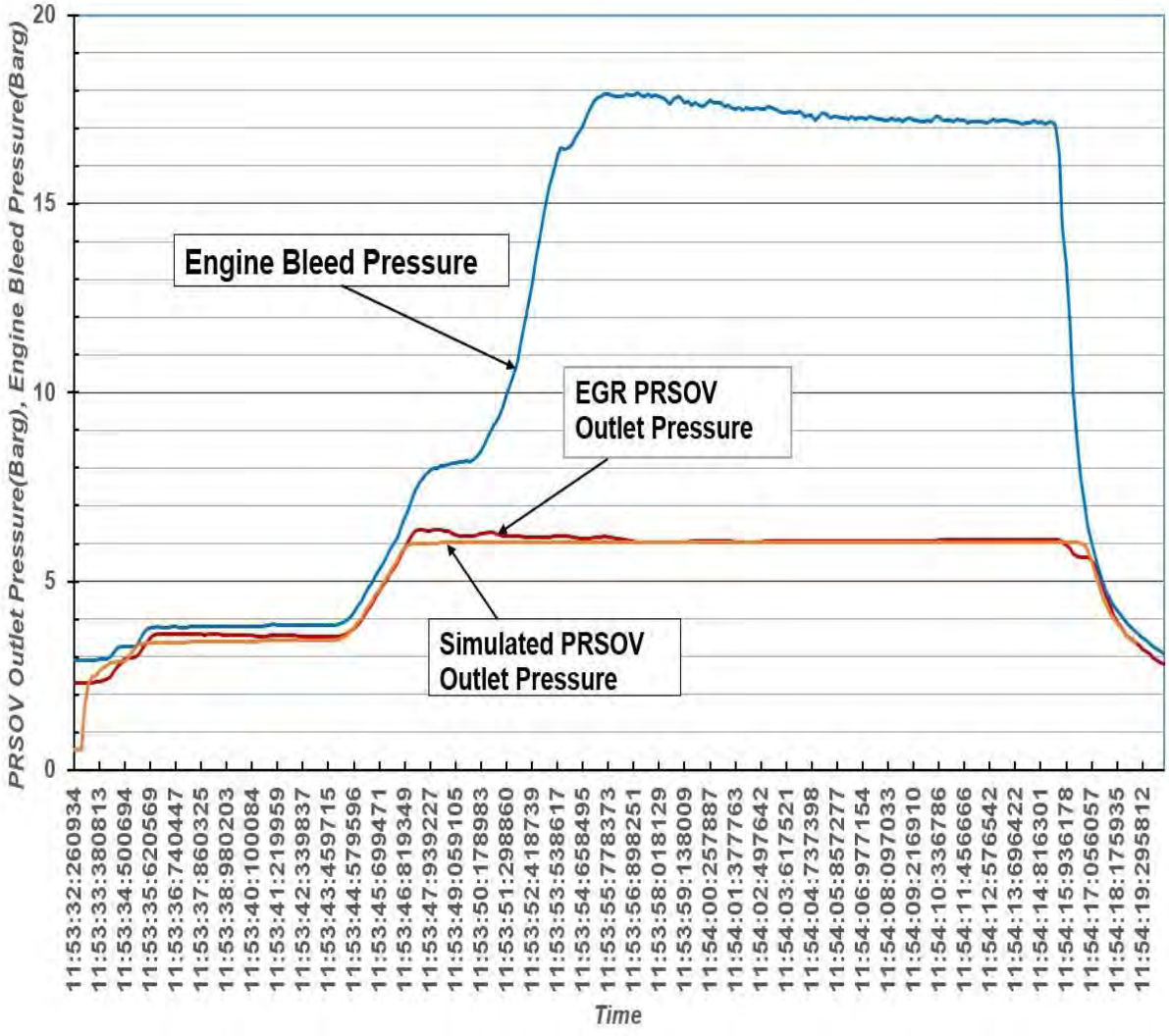

Figure 7: Comparison of PRSOV outlet pressure with Simulation results during transition to Engage state - Expanded portion – A of figure 3

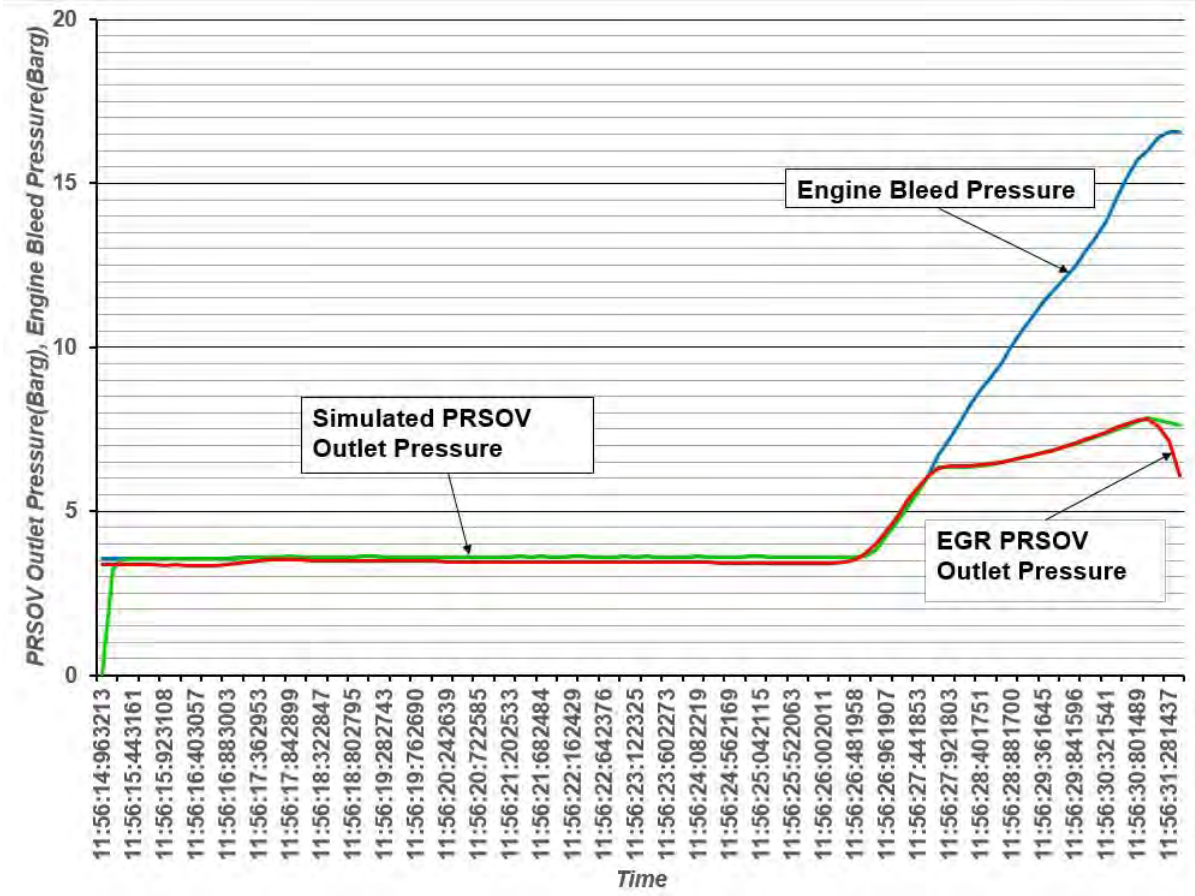

Figure 8: Comparison of PRSOV outlet pressure with Simulation results during Active state - Expanded portion – B of figure 3

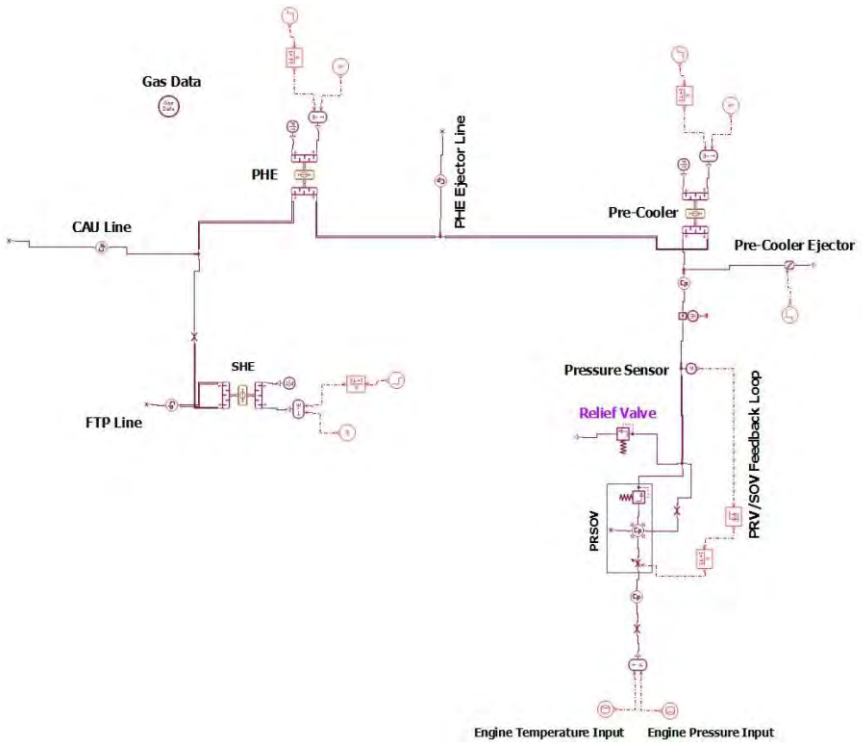

Figure 9: ECS system simulation architecture with Relief valve on Amesim platform

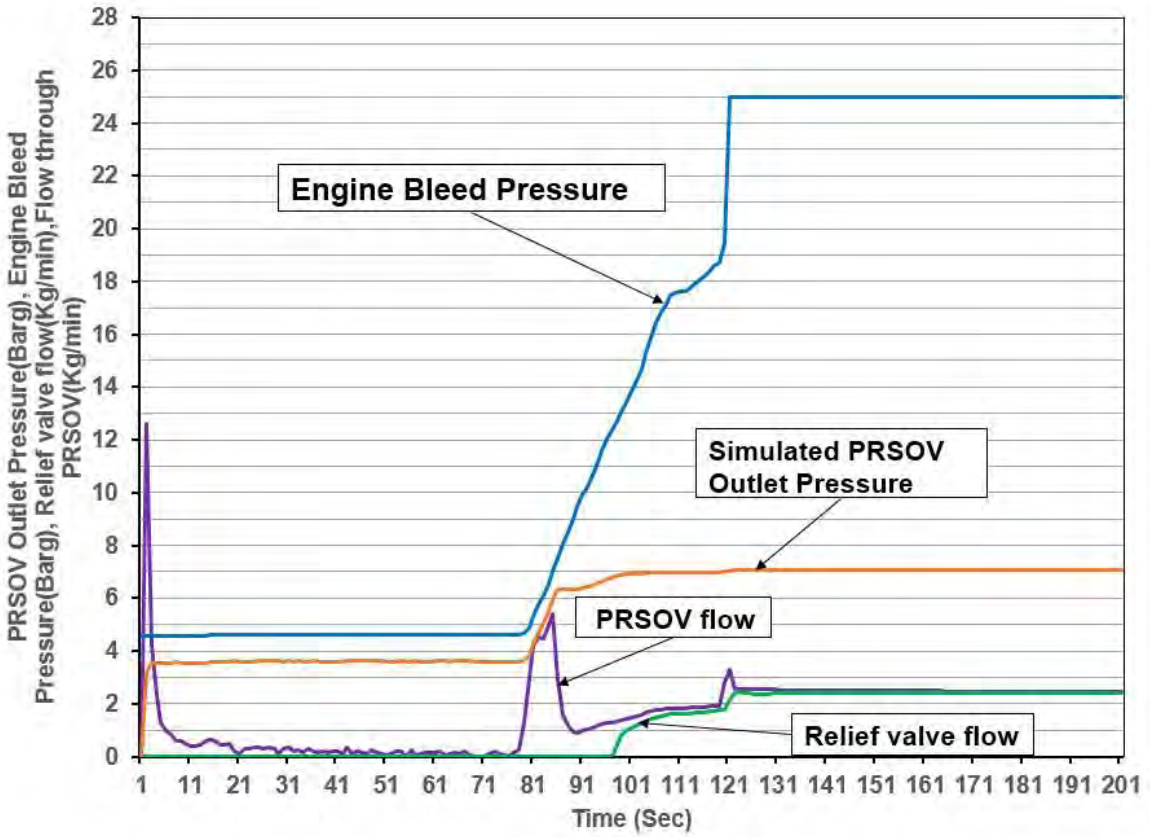

Figure 10: Simulation results with crack opening pressure 6.8 bar'g'

VI. Results & Discussion

Investigation is carried out to find the maximum relief flow and crack opening pressure during Active State. The Active state simulation results for crack opening pressure 6.8 bar'g' is plotted in Figure 10. Engine bleed temperature and pressure profile of EGR data is fed into the simulation as input. From simulation results, it is observed that with relief valve PRSOV downstream pressure stabilises at 7.07 bar'g' maximum (below the overpressure condition lower tolerance limit i.e. 7.15 bar'g') for the 25 bar'g' engine bleed pressure. For 6.8 bar'g' crack opening pressure, maximum relief valve flow is estimated as 2.5 kg/min. It is required to relive 2.5 kg/min of during Active state to avoid overpressure warning.

With Tolerance, crack opening pressure of relief valve can be considered as 6.8±0.05 bar'g'. With 6.75 bar'g' as crack opening pressure, the PRSOV downstream pressure stabilises at 7.02 bar'g' and for 6.85 bar'g' crack opening pressure, PRSOV downstream pressure stabilises at 7.1 bar'g'. It is simulated that with relief valve, Active state can be attained. A detailed component level simulation has already been worked out to arrive on the appropriate dimensions of relief valve. Thrust loss can be reduced from 2.5% (Engage State) to 0.75% in Active state with incorporation of relief valve during deck take off.

Acknowledgment

The authors acknowledge the Aeronautical Development Agency (ADA), Bengaluru for allowing them to publish this paper.

Nomenclature

LCA Light Combat Aircraft CAU Cold Air Unit CFD Computational Fluid Dynamics ECFM Environment Control and Fuel Management controller EGR Engine Ground Run ECS Environmental Control System ECSSOV ECS Shut Off Valve FTP Fuel Tank Pressurization PHE Primary Heat Exchanger PLA Power Lever Angle PRSOV Pressure Reducing and Shut Off Valve SHE Secondary Heat Exchanger

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Performance Evaluation on friction and wear behaviour of MoS2 Nano Additives with Military (MIL) grade Lubricant for Aerospace Applications

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Abstract - The lubricant in the aircraft power transmission accessory gearbox resulted in temperature rise and heat generation due to high frictional coefficient in the contact surfaces. To address this, the current research proposes the addition of MoS_2 nanoparticles to MIL grade lubricant as an additive to reduce the friction and wear. In this performance evaluation study, MoS_2 nanolubricant was prepared using various surfactants for better suspension of MoS_2 nanoparticles, and properties were evaluated for both base lubricant and nanolubricant. The experiments were carried out using a four-ball tester, a shear stability tester, and a reichert tester. In four-ball test, MoS_2 nanolubricant resulted in a 7.8 % reduction in frictional torque compared to the base lubricant. In shear stability test, MoS_2 nanolubricant showed 66.77% better shear stability performance than the base lubricant. In the reichert test, the coefficient of friction was reduced by 13% with the MoS_2 nanolubricant. The performance evaluation of both base and nanolubricant demonstrated that the MoS_2 nanoparticles, as an additive to a military standard lubricant, have superior frictional properties and shear stability for aerospace applications.

Keywords - aerospace; lubricant; MoS_2; nano-additives; performance;

I. INTRODUCTION

Performance evaluation of any aircraft system is a major step towards the airworthiness certification. Aircraft power transmission system is a critical system for which performance needs to be evaluated. Lubricant and its additives play a major role in the performance of the power transmission system. In general, wear is considered the most critical in any mechanical system, as it may lead to catastrophic failure [1]. Different lubricants are employed to overcome the wear from the frictional contacts of machine elements [2]. But, the development of lubricant for specific application is challenging for better results. The wear and thermo-physical properties of the lubricant can be substantially improved by the proportionate addition of nanoparticles as potential additives to the base lubricant [3]. The advancement in manufacturing methods of nanoparticles (NPs) paved the way for researchers to study the frictional characteristics of lubricants with nano additives. The study and application of NPs are very interesting but challenging in many aspects due to their size, quantum confinement, superior physical and chemical properties when compared with bulk

materials [4-5]. Many researchers have demonstrated that the nano additives like metals and metal oxides [6-9], metal sulphides [10-12], graphene [13-14], boron nitrides [15-18] with base lubricant resulted in reduced friction, wear and improved load carrying capacity. Molybdenum disulphide (MoS_2) has excellent friction and wear properties under inert or vacuum environments [19]. Studies have shown that the addition of MoS_2 nanoparticles improved the wear characteristics of the base lubricant oil [20-21].

MIL-PRF-23699 grade lubricant is used in the gas turbine engine gearbox, aircraft mounted accessory gearbox, and electrical generators for lubrication and cooling for military aerospace applications. This lubricant must perform satisfactorily in all aircraft's environmental conditions. The military standard (MIL-PRF-23699) specifies the lubricant's minimum and mandatory physical, chemical, and performance requirements [22]. During flight operations, an aerospace lubricant is subjected to a wide range of temperature, pressure, and speed [23].

From the open literature survey, there is no data available pertaining to the formulation and wear characteristics of MoS_2 nanolubricant with MIL-PRF-23699 grade lubricant. Hence, it is essential to undertake research in the field of MoS_2 based nanolubricants for aerospace applications. This will help to enhance the life of aircraft power transmission units, reduce energy loss and temperature rise by reducing friction. This article describes the physical characterization of MoS_2 NPs using SEM (Scanning Electron Microscope), XRD (X-Ray Diffractometer), Raman spectroscopy, TGA (Thermo Gravimetric Analyzer), and DSC (Differential Scanning Calorimetry). The preparation of a stable MoS_2 nanolubricant with various surfactants and the performance evaluation of lubricant properties are described. This article describes the effect of MoS_2 NPs on coefficient of friction (CoF), shear stability, and wear resistance with the results of the four-ball test, shear stability test, and a reichert test.

II. MATERIALS AND METHODS

A. Selection of base lubricant, Nanoparticle and Dispersant

MIL - PRF - 23699 grade lubricant was taken as base lubricant in this study. The lubricant properties like density, kinematic viscosity, flash point, fire point, and TAN (Total Acid Number) of the base lubricant (BL) were determined for base line reference. The Molybdenum disulphide (MoS2) NPs were used as an additive with MIL grade lubricant to prepare MoS_2 nanolubricant (NL). SEM, EDX (Energy Dispersive X-Ray), TGA, and DSC techniques were used to characterize the MoS_2 nanoparticles in terms of surface morphology, phase composition, and thermal stability. The XRD analysis was done using a Bruker make diffractometer and analyzed for the 2θ range of 10° to 100°. Raman spectroscopy analysis also carried out to ascertain the phases and crystal structure of the MoS_2 Nps.

Different types of surfactants, like Cetyl Trimethyl Ammonium Bromide (CTAB), Sodium Lauryl Sulphate (SLS), Oleic Acid (OA), and Poly Ethylene Glycol (PEG) have been adopted in the present studies and attempts were made to obtain stable dispersion and suspension of MoS_2 NPs in the base lubricant. Surfactants with stable nanoparticle dispersion and suspension were identified and used for further performance testing.

B. Preparation of nanolubricant and property evaluation

The ultrasonic probe sonication method (Q Sonica- Q- 1500) was used to prepare the MoS_2 nanolubricant (MoS_2 NL) with various surfactants. The surfactants (0.1% vol.) and MoS_2 NPs (0.1% wt.) were mixed with the required amount of base lubricant using manual stirring, followed by ultrasonic probe sonication for 1 hour. The MoS_2 nanolubricant was then subjected to a physical observation test to determine NP suspension stability over many days. The stable NP dispersion and suspension were identified from the group and used for finding the density, kinematic viscosity, flash point, fire point, and TAN of the

nanolubricant. Performance tests were performed on the stable nanolubricant, which had a better suspended NP.

III. FOUR BALL TEST

The four ball tester was used to measure the frictional torque of a chrome steel ball with both base lubricant and MoS_2 nanolubricant independently, as per the ASTM D2783 standard [24]. Three chrome steel test balls of diameter 12.7 mm were located within a lock ring and clamped by a hex-nut in the bottom cup and filled with lubricant. The fourth chrome steel test ball was held in a collet located within the spindle on the top. A schematic illustration of four ball tester is shown in figure 1.

The test-lubricant cup assembly with test balls was positioned on the test apparatus, aligning with the motor spindle. The spacer was placed in between the cup assembly and thrust bearing in the locators, which ensures alignment. The weight tray was fixed to the horizontal arm, and sufficient weights were placed as per the ASTM D2783 standard. The lever arm was released, and the test loads were applied gently to the balls. Shock-loading should be avoided as it may deform the balls permanently. The temperature of the lubricant was maintained between 18 and 35 °C.

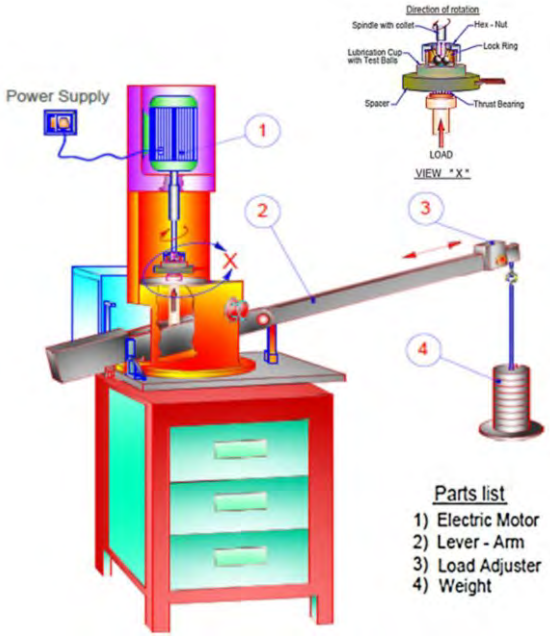

Fig. 1. Schematic illustration of Four ball tester

The frictional torque under various load conditions during an extreme pressure test for a base lubricant and MoS_2 nanolubricant was measured in the four-ball test.

IV. SHEAR STABILITY TEST

This test method is used to determine the shear stability of the base lubricant and nanolubricant, by measuring the percentacge viscosity loss of lubricant at 100 °C. The viscosity loss reflects the degradation of lubricant due to shear at nozzle.

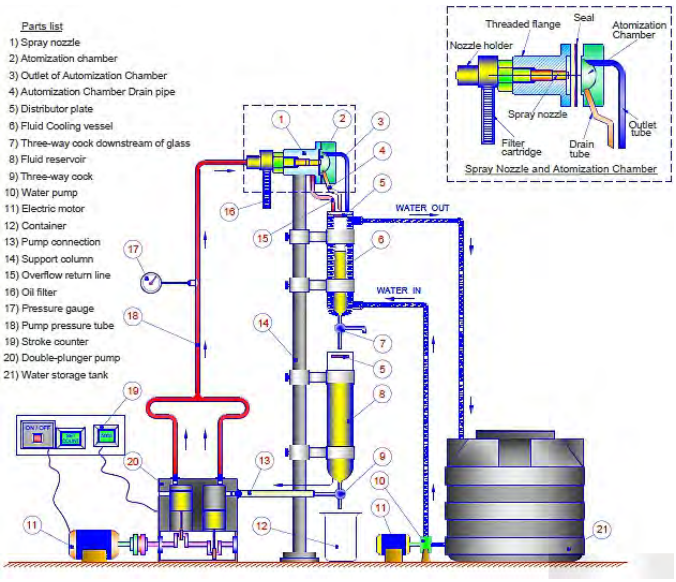

Fig. 2. Schematic illustration of shear stability tester

Figure 2 shows the schematic illustration of four ball tester. The shear stability test setup comprises a fluid reservoir, a double plunger pump powered by an electric motor, an atomization chamber with a spray nozzle, and a cooling vessel to keep the lubricant nearly constant temperature during the test. The fluid reservoir was filled with the test lubricant. The stroke counter was set to shut off automatically after the required number of impulses for 30 minutes. The volume of the fluid reservoir was assured. The pump was started, and the test lubricant was circulated for 30 minutes at the required pressure. Water was circulated in the cooling vessel to keep the test lubricant temperature at the reservoir's delivery point between 30 °C and 35 °C. After 30 minutes, the pump was turned off, the three-way cock beneath the fluid reservoir was opened, and the first 10 to 15 ml of waste fluid

was drained to flush it out, and the remaining fluid was collected in a sample container. By using a viscometer, the kinematic viscosity at 100°C of both sheared and un-sheared test fluids was determined.

The Percentage Viscosity Loss (PVL) of the BL and MoS2 NL was determined using the shear stability tester in accordance with ASTM D-6278 [25]. The PVL indicates the viscosity loss, reflecting lubricant degradation during operation.

V. REICHERT TEST

Reichert tester is developed to determine the CoF and wear loss of the specimen with block-on-ring configuration simulating the line contact with lubricant under various load conditions. The test apparatus consists of a spindle with a ring specimen clamped on it that is powered by an electric motor as shown in figure 3. The block specimen was placed on top of the ring specimen, making line contact. The block-on-ring arrangement with loading in the reichert tester. A lubricant jet was provided between contact lines of the specimens. The block was subjected to a load of 200 N at 1000 rpm for 30 minutes. With new sets of specimens, the experiments were carried out in steps of 100 N loads up to 500 N.

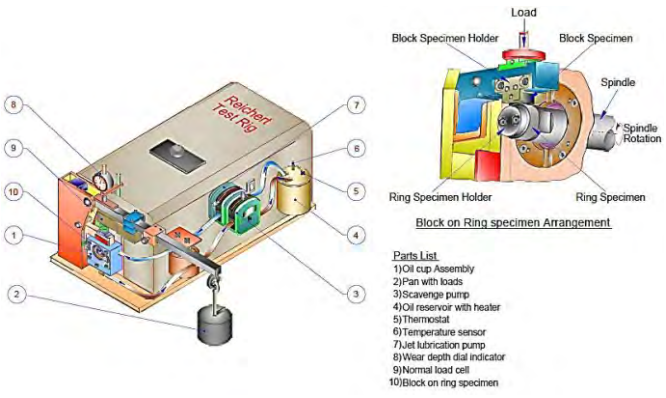

Fig. 3. Reichert Test Rig

The CoF was evaluated for various loads at a constant speed of 1000 rpm. The experiments were conducted with both base lubricant and nanolubricant. The comparison study was made to determine the better wear resistance between base lubricant and nanolubricant.

VI. RESULTS AND DISCUSSIONS

A. Characterization of MoS_2 nanoparticles

Prior to the preparation of the nanolubricant, it is necessary to characterize MoS_2 NPs in terms of physical and thermal stability. So, the morphology study was carried out for the MoS_2 nanoparticles and shown in figure 4. It was composed of nanosheets with hexagonal crystal structure, powdery in form, grey in colour. These nanosheets aids in adhesion of MoS_2 nanoparticles in the contact surfaces which avoids direct contact of rolling/ sliding surfaces.

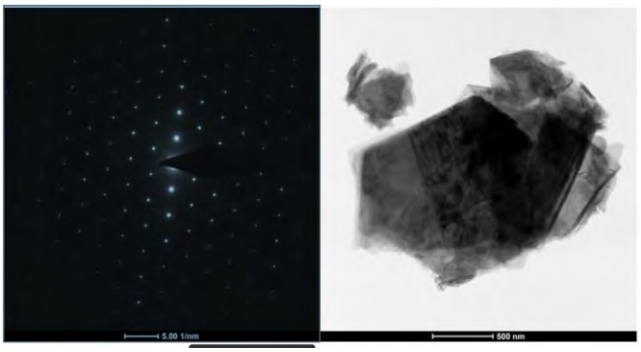

Fig. 4. Morphology analysis of MoS_2 nanoparticles

Raman spectroscopy was applied to ascertain the phases of the MoS_2 NP. The Raman spectra analysis shown in figure 5 depicts the characteristic peak at 175, 381, 405, 461 and 639 cm^{-1}, which correspond to the high frequency vibrating mode of MoS_2. This evidences MoS_2 particles having an orderly crystalline structure, which is in line with XRD analysis.

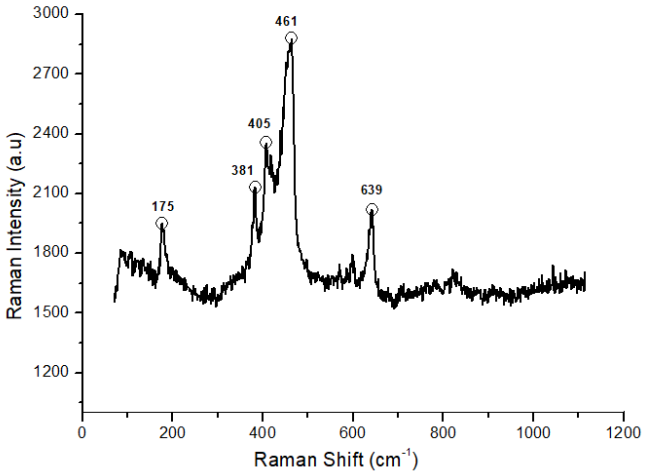

Fig. 5. Raman spectra analysis of MoS_2 nanopartic

B. Physical Characterization of MoS_2 nanolubricant

Base lubricant containing 0.1% wt. MoS_2 NPs and no surfactant was stable for 127 days. However, various surfactants were tested to see if they could improve NP stability further. The addition of PEG surfactant (0.1% vol.) was found to be as effective as no surfactant at all. MoS_2 NPs were only stable for 104 days in other cases where SLS and CTAB were added to the base lubricant. The MoS_2 NPs were stable for 115 days after an OA surfactant was added to the basic lubricant. Surfactants had no discernible effect on nanoparticle stability. As a result, the nanolubricant made with 0.1% wt. MoS_2 NPs without any surfactants that was stable for 127 days was chosen for further study and frictional inquiry.

C. Four ball test results

The four ball tests were performed to measure frictional torque in accordance with ASTM D2783-03. Figure 6 depicts the frictional torque under various load conditions during an extreme pressure test for a base lubricant and a nanolubricant.

It is observed that the chrome steel balls exhibited low frictional torque at lower loads in both BL and MoS_2 nanolubricant. The formation of lubricant film was the primary cause for low frictional torque. The lubricant film has prevented asperity-asperity contacts, lowering the frictional torque. With increasing load, the frictional torque of the chrome steel balls increased in both base lubricant and MoS_2 nanolubricant.

As a result of the high contact pressure developed at higher load conditions, the asperities' contact has increased, resulting in a higher frictional torque for the chrome steel balls. As the load increased, the frictional torque in the MoS_2 NL was lower than BL. During the lower load conditions, the MoS_2 NL had little effect on the frictional torque compared to BL. However, as the applied load was increased, the frictional torque in MoS_2 nanolubricant decreased significantly compared to the BL. Importantly, the frictional torque in the MoS_2 nanolubricant was 7.8% lower than BL at 1600 N load.

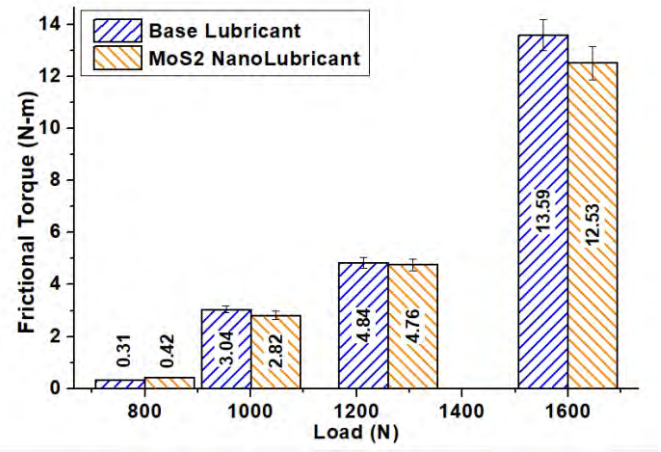

Fig. 6. Comparison of frictional torque with BL and MoS_2 NL

The primary reason for the decrease in frictional torque was attributed to the nano-lubrication mechanism provided by the NP. The presence of MoS2 NPs formed tribofilm between the chrome steel balls at higher load conditions resulting in decreased frictional torque compared to the base lubricant.

D. Shear stability test results

This test was performed to examine the effect of adding nanoparticles to the base lubricant on shear stability of lubricant. The comparison plot of percentage viscosity loss of base lubricant and MoS_2 nanolubricant is shown in figure 7. For the base lubricant, the kinematic viscosity was dropped significantly from 5.09 cSt to 4.94 cSt in the shear stability test. The base lubricant lost nearly 2.95 % of its viscosity. The primary cause of the decrease in viscosity is the degradation of polymer chains in the base lubricant. The decrease in viscosity also indicates that the base lubricant experienced permanent shear thinning. Shear thinning effects are classified into two types: temporary shear thinning and permanent shear thinning. When shear stress is applied to a polymer, it tends to stretch and then return to its original position when the shear stress is removed. In cases of permanent shear thinning, the polymer chain tends to break and does not return to its original state.

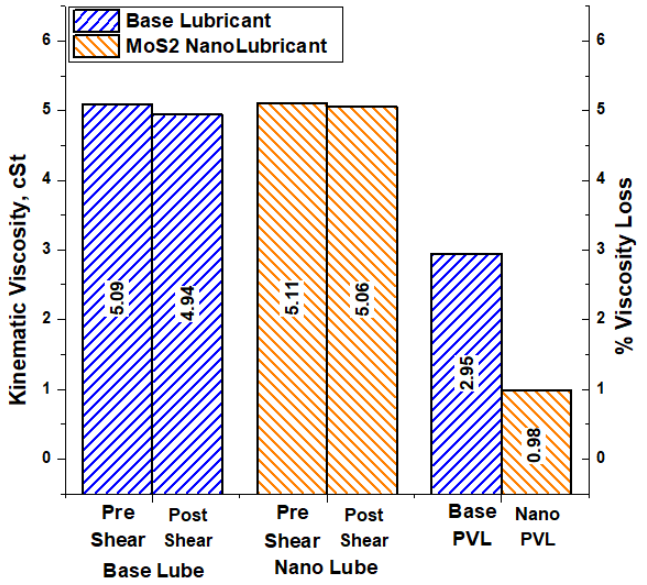

Fig. 7. Comparison of PVL of BL and MoS_2 NL in shear stability test

The same experiment was conducted with MoS2 nanolubricant. The kinematic viscosity of MoS2 nanolubricant was 5.11 cSt, which was slightly reduced to 5.06 cSt after the test. The MoS_2 NL lost only 0.97% of its viscosity, indicating better shear stability. It was noticed that the nanolubricant has 66.77% greater shear stability than the base lubricant. The reason for nanolubricant's better shear stability is due to its higher shear load carrying capacity during shearing action, which prevents viscosity loss of the lubricant.

E. Reichert test results

The reichert tests were conducted at different load conditions of 200 N, 300 N, 400 N, and 500 N for duration of 30 minutes, and at a constant speed of 1000 rpm. The comparison plot of the coefficient of friction of base lubricant and nanolubricant is shown in figure 8.

At different load conditions of 200 N, 300 N, 400 N, and 500 N the reduction observed in CoF of MoS_2 nanolubricant was 38.46%, 13.33%, 15% and 13.04% compared to the base lubricant. It is found that the influence of MoS_2 NPs in nanolubricant is more effective at lower loads in reduction of CoF. Compared to the higher loads MoS_2 showed the best reduction value of 38.46% at 200 N load condition when compared with base lubricant.

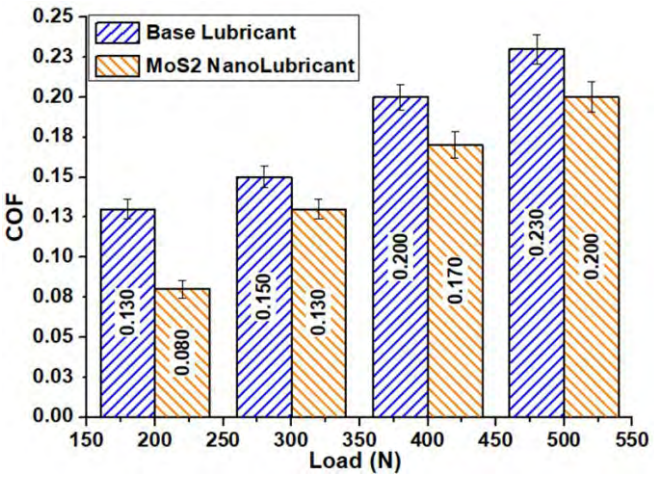

Fig. 8. Comparison of CoF between BL and MoS_2 NL- Reicher test

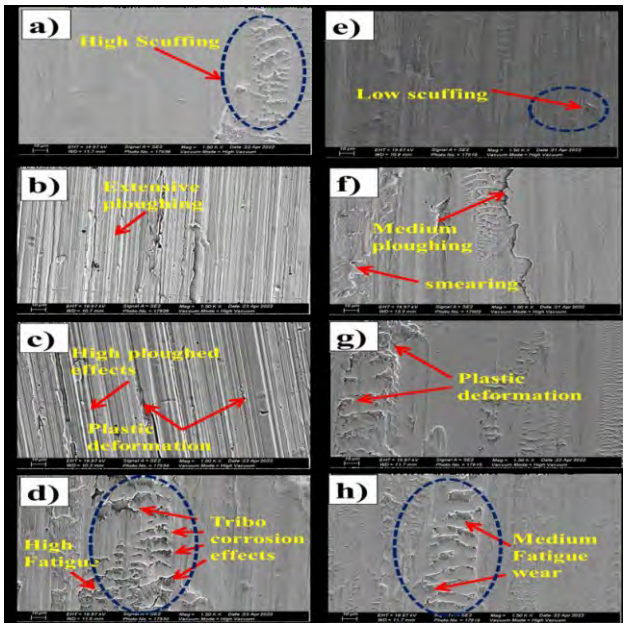

Fig. 9. (a-d) SEM image of wear scar in BL, (e-h) SEM image of wear scar in MoS_2 NL

To further extend the wear characterization, SEM image analysis was carried out on wear scars formed with BL and shown in figure 9 (a-d). It is very clear that the damages in the wear track increased with deep grooves as the load increased. SEM revealed that the wear mechanisms in the BL condition were high scuffing, extensive ploughing, tribocorrosion, and fatigue wear. This was due to increased contact stress, temperature rise, chemical reactions, and tearing of tribofilm at the true contact surfaces under high load conditions, resulting in extensive surface wear.

Similarly, SEM image analysis was also carried out on wear scars formed with nanolubricant and shown in figure 9 (e-h). In the MoS_2 NL condition, SEM revealed low scuffing, low ploughing, smearing, and less tribocorrosion with smooth surfaces and signs of fine scratches compared to the base lubricant. The ability of MoS_2 nanoparticles to adhere with mating surfaces and rolling abilities form a physical tribo-layer. This tribolayer prevented the specimens from making true contact, resulting in less adhesive wear, less tribocorrosion, less smearing, and scuffing. As a result, for the same load consideration, MoS_2 nanolubricant showed less wear than base lubricant wear, proving NPs assist for the improvement in wear resistance of the specimen.

VII. CONCLUSION

In summary, MoS_2 nanolubricant was developed by ultrasonically mixing MoS_2 nanoparticles in MIL grade base lubricant (MIL-PRF-23699) with various surfactants. MoS_2 nanoparticles were discovered to be very stable and better suspended in MIL grade base lubricant without any surfactants. When the lubricant properties of base lubricants and nanolubricant were evaluated, it was revealed that the physical and thermal properties of both lubricants were nearly identical. Performance tests were performed for the base lubricant and the nanolubricant in a four-ball tester, a shear stability tester, and a reichert tester. The results were as follows:

- In the four-ball test, the MoS_2 nanolubricant was found to have a 7.8% reduction in frictional torque.
- In the shear stability test conducted for both the base lubricant and the nanolubricant, the MoS_2 nanolubricant found to outperform the base lubricant by 66.77%.
- In the reichert test, MoS_2 NL exhibited 13% reduction in CoF compared to base lubricant at 500 N load The wear scar images from the optical microscope and SEM revealed a decrease in the mean wear scar width, attributes to better wear resistance.

The performance tests demonstrated that MoS_2 NPs are a promising nano additive for MIL grade lubricants, improving friction and wear resistance for low-carbon alloy steel used in aerospace applications and also enhancing shear stability of lubricant. However, different types of nanoparticles such as TiO_2, Graphene etc., have to be investigated for aerospace grade lubricant as a future focus of this research. The performance evaluation of nanolubricants was carried out at specimen level and it can be extended to the aircraft accessory gearbox level in the test rigs.

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Effect of Residual stress on creep behavior for In718 Superalloy of TIG welded joints

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Abstract - The nickel-based superalloy of IN718 is widely used in aero engines for their excellent thermal stability at elevated temperatures. These alloys are precipitation hardenable alloys, it has good weldability property and creep resistance. The welded sheets experience distortions effect after welding. The residual stresses are also induced in the weld zone, HAZ and interface of both. Most of the aero engine parts of the combustion chamber and outer casing are made up of welded joints. The weld joints are required to be characterized for material design allowables. The weld zone showed a higher hardness value of 436 HV0.1 for the AS weld and 586.3 HV0.1 for the PWHT sample. A study on the creep behavior with the accumulated residual stress for a defined time and temperature parameters up to 200 h is carried out. The combustion chamber and outer casing of an aero engine experience a temperature range from 550 °C to 700 °C. The creep test is carried out in this range to study the effect of residual stress on the creep life. These alloys exhibit good creep resistance and microstructural stability at elevated temperatures. All the parameters play a significant role in reducing the failure of an aero engine.

Keywords - TIG welding, Distortions, Residual Stress, Creep Life.

I. INTRODUCTION

The aero engines are the primary part of the aircraft, which is exposed to thermal loads during its operation. The materials used in the aero engines are nickel-based superalloys, titanium-based super alloys and steels [1]. The combustion chamber and outer casing are exposed to high temperatures during operation, hence, they are made up of nickel-based superalloys [2, 3]. Aero engines are made up of different joining techniques of these superalloys. Most parts of aero engines, such as the combustion chamber and outer casing are made up of welded joints [4]. These joints need to be quantified to know the strength and life of the welded joints. One of the traditional methods of welding is tungsten inert gas (TIG) welding, which is carried out for welding

the combustion chamber and outer casing of an aero engine. Proper data for the designers needs to be provided regarding the creep life of the sample. The stresses are induced in the welded joint during welding in the welded zone, Heat affected zone (HAZ) and base material. IN718 has good weldability properties due to the presence of minimal amount of aluminium and titanium [5]. The material IN718 is widely used for TIG welding in the combustion chamber and outer casing [6]. The thin sheets of IN718 are welded by the TIG welding method. Distortions are induced in the sheets due to the rapid cooling effect and solidification of the weld pool. TIG welding has non-consumable electrodes, i.e. made up of tungsten. These distortions are significant limitations for the thin sheets incorporated in an aero engine's combustion chamber and outer casing. The geometrical imperfection with residual stresses in the sheets enhances brittle failure and crack initiation during fatigue. Due to stress induced in the welded sheets, distortions are observed, which are of two types radial and angular distortions or a combination of both. A proper selection of weld parameters is required to minimise the distortions in the sheets. As per the American Welding Society (AWS) standards, Welding parameters need to be carried out to optimize the distortions and stress levels in the sheets. The hardness profile has been observed over the length of the sheet. The welded joints' residual stresses are measured using the X-ray diffraction technique [7, 8]. The creep behavior of the welded joints also has a crucial role in deformation and failures during exposure to variable thermal loads [9, 10].

II. THEORETICAL BACKGROUND

A. Distortions induced in the welded sheets

The distortions formed in the welded sheets during welding are of two types radial and angular distortions or a combination of both, as shown in Figure 1 (a). These distortions also have some residual stresses induced in them. The thin sheets of IN718 are welded by the TIG welding method. Distortions are generated in the sheets due to the rapid cooling effect and solidification of the weld pool. Improper clamping effect also has an impact on the distortions in the sheets.

These distortions are to be minimized to reduce the failure of an aero engine during operation. These distortions have major limitations for the thin sheets incorporated in an aero engine's combustion chamber and outer casing. The geometrical imperfection with residual stresses in the sheets enhances brittle failure and crack initiation during fatigue. Optimizing the weld parameters for reducing the distortion levels is a challenging part. The distortions are measured using weld gauges and represented in the coloured contour. Both radial and angular distortions are observed, as shown in Figure 1 (b). The welded sheets are distorted more due to the welding of a lengthier sheet of 210 mm. Heat input and cooling time were higher, leading to higher distortion levels.

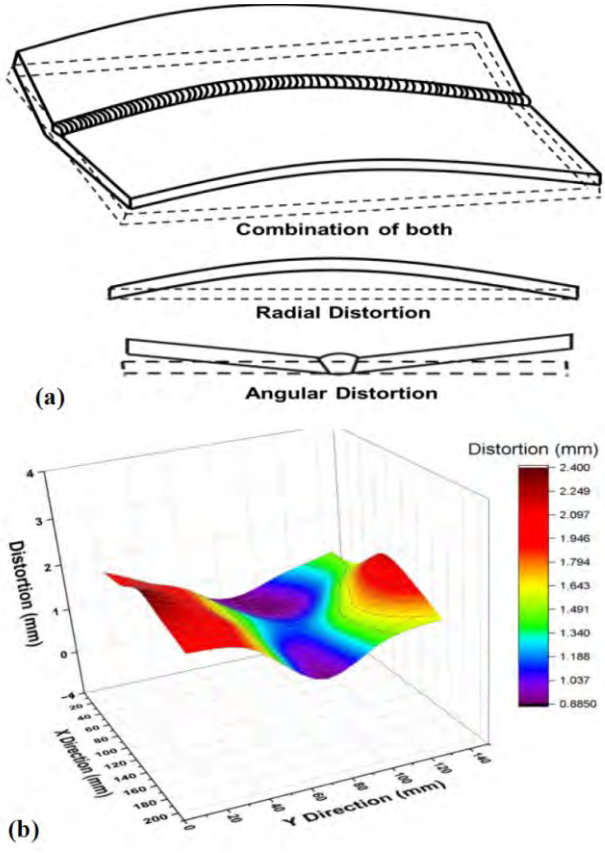


Figure 1: The types of distortion in the TIG welded IN718 sheets are a) Combination of both distortions, radial Distortion and Angular Distortion, and b) Distortion measured for IN718 sheets.

B. Residual stress

The residual stresses are measured through the sample's surface using a non-destructive method. The residual stresses are based on the principle of the X-ray diffraction technique. Manganese tube K-α source is used for measurement using the X-ray diffraction method by the machine iXRD (Proto). The residual stress is induced in the welded sheets after rapid cooling of the welded sheets [11]. The Parameters affecting residual stress growth are improper welding procedure and insufficient clamping force on the sheets. These residual stresses need to be optimized and lowered as much as possible to prevent the failure of welded joints. Residual stress also leads to the formation of heat cracks in the weld and HAZ zone during exposure to thermal loads.

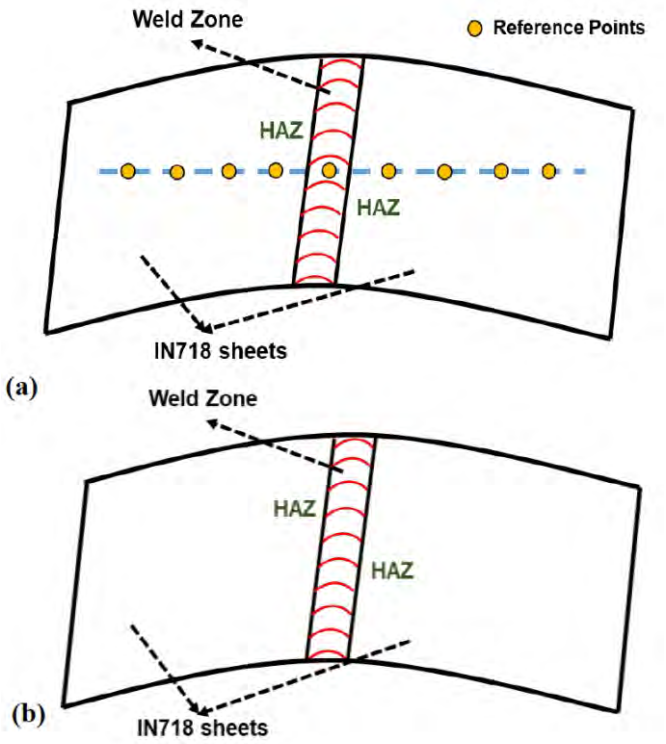


Figure 2: The IN718 TIG welded sheets are a) Base welded sheets and b) Reference points selected over the welded sheet for residual stress measurement.

It is observed in Figure 2 (a) the different zones in the welded sheets, i.e. weld zone, HAZ and base material. The reference points taken from the middle section of the sheets are shown in Figure 2 (b), which has both angular and radial distortions induced. Around nine reference point locations are identified and measured for residual stress induced in them. The measurement of the residual stress is very important to prevent an aero engine's failures.

III. EXPERIMENTAL OBSERVATIONS

A. Welding of IN718 sheets

The initial heat treatment of the IN718 sheets is hot rolled and solution heat treated. The TIG welding of IN718 is carried out for the sheets of dimensions 100 mm x 50 mm x 2.3 mm each. The welding is carried out according to American Welding Society (AWS) standards for weld power, speed, root gap, and angle. The type of filler rod used for joining the sheets is ERNiFeCr-n, with a diameter of 2.4 mm. The current of 110A and 12 Volts voltage is used as input parameters for the welding machine (Indus-Arc, TIG-320 iPA). The root gap between the two sheets is 2.4 mm for better penetration of the molten weld pool between the sheets. Argon gas purging at the rate of 8-10 lpm prevents the oxidation of the welded joints and reduces distortion levels. The welding speed around 4.1 mms-1 is carried out. The welding parameters used for TIG welding of an IN718 super alloy are shown in Table 1.

Table 1: TIG welding input parameters used for IN718 super alloy as per AWS standards.

Pass		1
Filler Metals	**Process**	TIG
	Class	ERNiFeCr-2
	Diameter (mm)	2.4
Current	**Type**	AC
Voltage	**Volts (V)**	12
Speed	**(mm/sec)**	4.1

B. Post Weld Heat treatment of welded joints

The IN718 hot rolled solution heat-treated sheets are TIG welded according to the AWS standards. After welding, some angular and radial distortion are observed in the sheets. To minimize the effect of distortion in the sheets, post-weld heat treatment (PWHT) is carried out with double ageing heat treatment conditions [12]. The PWHT cycle has a two-step ageing process after the solutionizing of the sheets, as shown in Figure 3. The solutionizing temperature at 1080 °C is carried out initially to the sheets. Welded sheets are double aged at 720 °C for 8 h with furnace cooling at the rate of 0.5 °C/min and ageing again at 620 °C for 8 h and cooling at atmospheric conditions. By this PWHT cycle, the material's strength is increased by enhancing some of the mechanical properties. The precipitate strengthening of IN718 by this double ageing process is obtained due to the formation of γ´ and γ´´ precipitates.

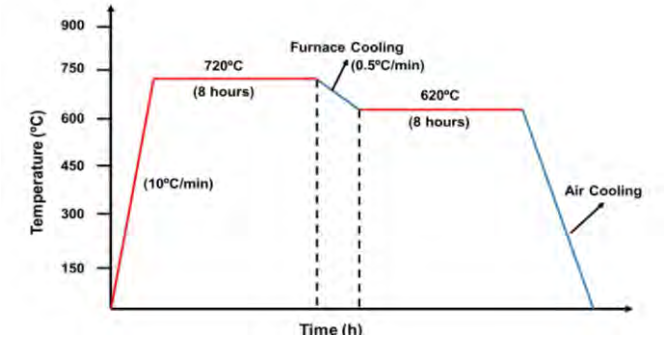


Figure 3: The PWHT cycle for IN718 TIG welded sheets

IV. RESULTS AND DISCUSSION

A. Micro hardness Measurement

The Vickers hardness measurement is carried out in the Wilson VH1202 microhardness testing machine. The hardness has been taken for both AS weld condition and Post weld heat treatment condition (PWHT) [12, 13]. Two-stage ageing heat treatment is carried out to minimize the effect of residual stress and increase the hardness value of TIG welded sheets. As shown in Figure 4, the hardness value is higher at the welded zone and reduces gradually when it is away from the weld pool zone in both cases. The Weld zone has a higher hardness value due to rapid solidification of the molten pool. In the PWHT condition, hardness in the weld zone is increased compared to the AS weld condition. Dynamic recrystallization forms a fine-grain structure by increasing the material's hardness. The defects are more in the weld zone in AS weld condition, and these defects are removed by processing annealing treatment as mentioned in the heat treatment cycle. There are slight decreases in hardness value in the HAZ region compared to the weld due to the grain growth during the welding. The maximum hardness value is observed in the welded region for AS weld 436.8 HV0.1 and 586.3 HV0.1 for the PWHT sample, as shown in Figure 4. HAZ region also experienced hardness of 330.5 - 353 HV0.1 for AS weld condition and 507.5 - 557 HV0.1 for PWHT condition. The base region has a minimal hardness value of 293.4 - 324.7 HV0.1 for AS weld condition and 446.8-522.8 HV0.1 for PWHT condition. Due to the double ageing heat treatment process, there is an increase in the hardness value due to the presence of Ni3Nb (γ") and Ni3(Al, Ti) (γ') precipitates. Along with these precipitates, secondary phase Ni3Nb (δ) are also formed during PWHT. The presence of these phases increases the mechanical properties of the welded sheets.

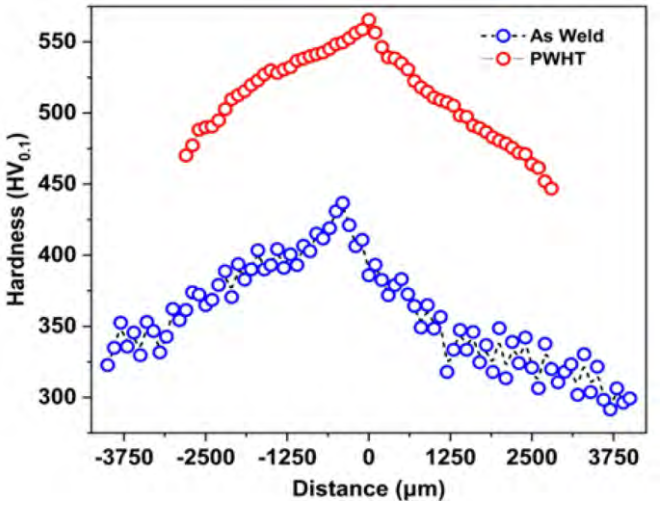


Figure 3: The PWHT cycle for IN718 TIG welded sheets

Zones/ Hardness Value	As Weld (HV0.1)	PWHT (HV0.1)
Weld Zone	436.8	586.3
HAZ	330.5-353	507.5-557
Base Material	293.4-324.7	446.8-522.8

Table 2: The hardness value for the AS welded and PWHT conditions of IN718 superalloy

B. Residual Stress Measurement

The residual stress is developed in the welded sheets due to non-uniform heat distribution. The welded region undergoes expansion and contraction of the molten pool, which gives rise to high residual stress of tensile. Tensile stresses in the material lead to the brittle fracture of the material. HAZ is affected during the welding due to exposure to the high temperature of the molten pool. Base material experiences most minor heat exposure and has minimal residual stress. Improper welding parameters input and clamping force will give rise to residual stress in the welded sheets. The residual stress measurement is carried out on the nine reference points on the TIG welded sheets by Proto iXRD machine. These sheets had both radial and angular distortions induced in it, comprising high residual stress in the welded region, as shown in Figure 5. These residual stresses need to be minimal to prevent the failure of an aero-engine component. The welded zone showed high residual stress up to 500 MPa, and the HAZ region decreased the residual stress up to 64.6 ± 6.8 – 71.3 ± 7.4 MPa. It is observed that there is little increase in the residual stress away from the HAZ region up to 190 MPa. In the base region, compressive stresses are observed up to -31.6 MPa. The heat treatment process can reduce this residual stress induced in the welded joints. After post-weld heat treatment (PWHT) of IN718 welded joints, the residual stresses are reduced to compressive stresses by eliminating tensile stress. In the welded zone, the tensile stress of 507 MPa has been reduced to -152 MPa, as shown in Figure 5. All the tensile stress developed in and around the welded region has been reduced and converted to compressive stress, which will increase the strength of the material by this heat treatment cycle. This PWHT also has a significant role in increasing the hardness and the creep life of the sample. The maximum residual stress obtained in compressive stress is -363 Mpa.

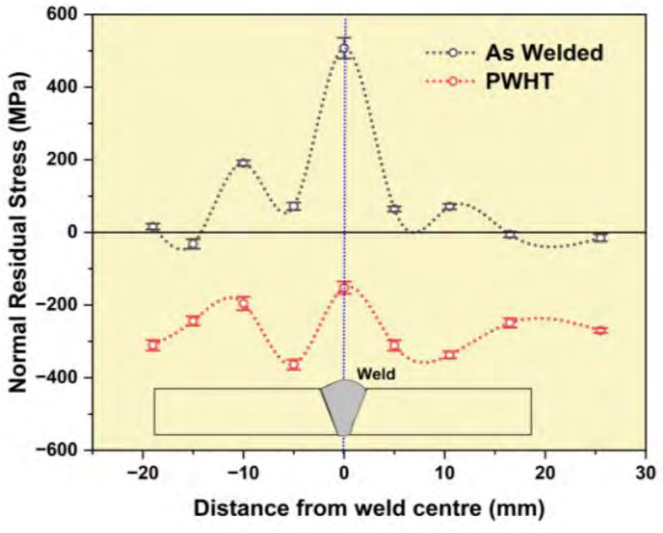
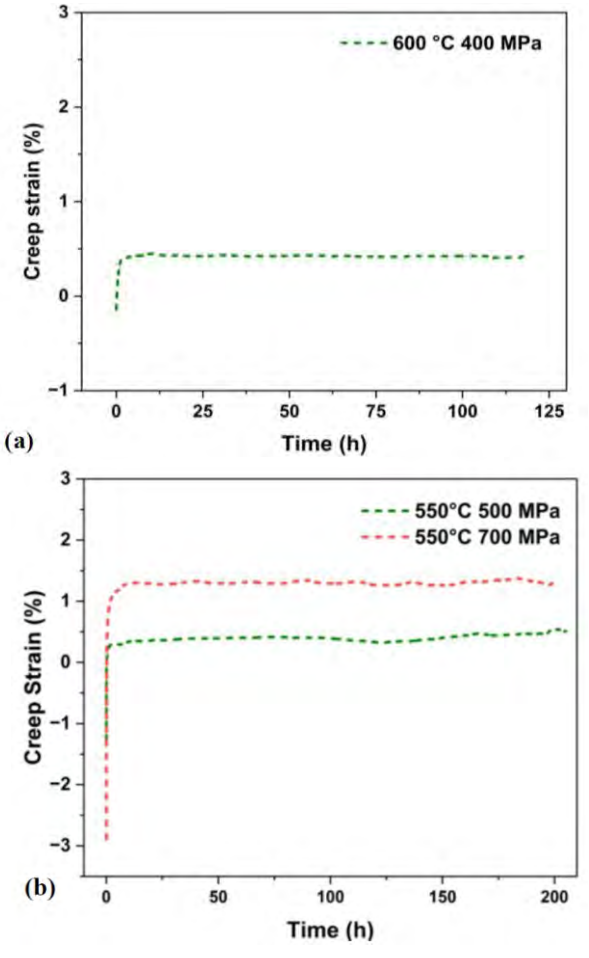


Figure 5: Residual stress measurement from the weld joint interface for IN718 welded sheet.

C. Creep behavior for IN718 TIG welded joints

The creep data have a significant role in predicting the life of the welded samples exposed to thermal loads during the operation of an aero engine. The creep behavior for IN718 TIG welded joints are studied for temperatures 550 °C, 600 °C and 650 °C and stresses of 400 MPa, 500 MPa and 700 MPa are carried out for both AS welded and PWHT condition. The samples are extracted from the middle of the welded sheets.



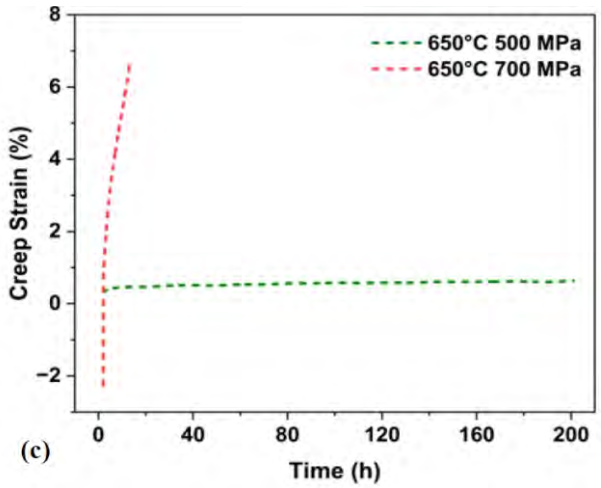


Figure 6: Creep behavior of IN718 a) AS Welded sheet, b) low temperature and c) high temperature.

The creep test for AS weld condition is carried out at 600 °C and 400 MPa up to 125 h. The creep strain obtained was in the range of up to 0.5 %. Since the AS welded material, which is solution heat treated, has less strength, it has been tested at a low stress level compared to the PWHT creep samples. In the case after PWHT, for low temperature and low stress, the creep strain is less than 2% and for a higher temperature range of 650 °C is up to 7 %, as shown in Figure 6. Only a secondary creep stage up to 200 h is observed in the low-temperature range, whereas in the high-temperature and high-stress tertiary stage creep is observed. Transition to the tertiary creep stage for a low-temperature range of 550 °C has more creep lifetime than the high-temperature range. The creep life for 650 °C and 700 MPa showed a minimal creep life of 12 h with creep strain up to 6.9 %. If the residual stresses are induced more in the creep sample, it leads to a minimal creep life of the specimen. It is observed after the sample's PWHT creep life is increased and creep strain is lesser at higher stress levels in the range of 500 MPa. The formation of □□ and □□□ precipitates after PWHT increased the strength of the material, leading in increasing the life of the sample. Eliminating the residual stresses by PWHT also directly affects the creep life by enhancing the strength of the material due to compressive stresses.

CONCLUSION

The aero engines are exposed to repetitive thermal loads during their operation. The aero engine components, such as the combustion chamber and outer casing, are made up of welded joints. These joints need to be quantified by the designers. The distortions, hardness, residual stress and creep life study have significant roles in designing an aero engine to prevent catastrophic failures. The distortions are minimized by following the AWS procedure for TIG welding. The hardness for AS weld 436.8 HV0.1 and 586.3 HV0.1 for PWHT is maximum in the welded zone, gradually decreasing in hardness when measured away from weld zone to base material up to 293.4 - 324.7 HV0.1 for AS weld condition and 446.8-522.8 HV0.1 for PWHT condition. The residual stress measured at nine reference points showed higher stress values up to 500 MPa in the welded zone. Away from the weld zone, compressive stresses are also observed up to 31.6 MPa in AS weld conditions. After PWHT, the residual stresses in the tensile nature are reduced to the compressive stage and increase the properties of the sample. The creep study is carried out from the samples extracted from the TIG welded sheets before and after PWHT for different stresses and temperature ranges. The creep strain for the AS welded condition is higher than the PWHT condition. Lower temperature showed a secondary creep stage up to 200 h creep life without any tertiary stage. Higher temperatures of 650 °C and 700 MPa showed tertiary stage with creep fracture at 6.9 % creep strain for 12 h creep life. These parameters are most important for designing an aero engine and preventing catastrophic failure when exposed to variable thermal loads.

ACKNOWLEDGMENT

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Manuscript Title: Effect of Residual stress on creep behavior for IN718 Superalloy of TIG welded joints

Answer to comments: Reviewer 2

Sl. No.	Comments/ Responses/ Corrections	
1	Reviewer comments	(a) paper ref. : Abstract—.....these joints are to be quantified for the designers. (b) Comment: The sentence may be modified as below: The weld joints are required to be characterized for material design allowables.
	Authors Response	The sentence is modified in the abstract section.
	Change in the manuscript	The weld joints are required to be characterized for material design allowables.
2	Reviewer comments	(a) paper ref. : Fig.2 (b) Comment Fig 2. Caption of the figure to be placed properly. Nine reference points for residual stress measurement are mentioned in the text but only seven points are shown in the Figure 2 (b).
	Authors Response	The caption and reference points are corrected.
	Change in the manuscript	The caption of the figure is corrected. The number of reference points is corrected in Figure 2 (b)
3	Reviewer comments	(a) paper ref.: III. EXPERIMENTAL OBSERVATIONS (b) comment: IN718 alloy sheet's heat treatment condition before welding is to be mentioned in the paper. (cold rolled and solution heat treated or only cold rolled – it may be verified) As it is stated that the weld joints were subjected to PWHT, details of PWHT heat treatment cycle (double aging) may be mentioned in this section of the paper
	Authors Response	The heat treatment condition is included in this section and explained in detail.
	Change in the manuscript	The IN718 hot rolled solution heat-treated sheets are TIG welded according to the AWS standards. After welding, some amount of angular and radial distortion is observed in the sheets. To minimize the effect of distortion in the sheets, post-weld heat treatment (PWHT) is carried out with double ageing heat treatment conditions. The PWHT cycle has a two-step ageing process after the solutionizing of the sheets, as shown in Figure 3. The solutionizing temperature at 1080 °C is carried out initially to the sheets. Welded sheets are double aged at 720 °C for 8 h with furnace cooling at the rate of 0.5 °C/min and ageing again at 620 °C for 8 h and cooling at atmospheric conditions. By this PWHT cycle, the strength of the material is increased by enhancing some of the mechanical properties. The precipitate strengthening of IN718 by this double ageing process is obtained due to the formation of γ′ and γ′′ precipitates.
4	Reviewer comments	(a) paper ref.: IV. RESULTS AND DISCUSSION A. Micro hardness Measurement HAZ region also experienced hardness of 330.5 - 353 HV0.1 for AS weld condition and 507.5 - 557 HV0.1 for As weld condition. The base region has a minimal hardness value of 293.4 - 324.7 HV0.1 for the AS weld condition and 446.8-522.8 HV0.1 for the PWHT condition.

Sl. No.	Comments/ Responses/ Corrections	
		(b)Comment 507.5- 557 HV0.1 harness may be pertaining to PWHT condition. The text may be corrected suitably. Also, the metallurgical reasons accountable for the hardness profile (change of hardness) in a given material condition (as welded / PWHT) may be explained here. In the absence of an explanation, it reads as only a data presentation. Fig 3 caption may be "distance from the weld joint interface"
	Authors Response	The text of the PWHT condition is corrected. Metallurgical reasons are addressed for the hardness profile.
	Change in the manuscript	The Weld zone has a higher hardness value due to rapid solidification of the molten pool. In the PWHT condition, hardness in the weld zone is increased compared to the AS weld condition. Dynamic recrystallization occurs, leading to the formation of a fine-grain structure that increases the hardness of the material. The defects are more in the weld zone in AS weld condition, and these defects are removed by processing annealing treatment as mentioned in the heat treatment cycle. There are slight decreases in hardness value in the HAZ region compared to the weld due to the grain growth during the welding. HAZ region also experienced hardness of 330.5 - 353 HV0.1 for AS weld condition and 507.5 - 557 HV0.1 for PWHT condition. Due to the double ageing heat treatment process, there is an increase in the hardness value due to the presence of Ni3Nb (γ'') and Ni3(Al, Ti) (γ') precipitates. Along with these precipitates secondary phase Ni3Nb (δ) are also formed during PWHT. The presence of these phases leads to an increase in the mechanical properties of the welded sheets.
5	Reviewer comments	(a) paper ref.: IV. RESULTS AND DISCUSSION B. Residual Stress Measurement The heat treatment process can reduce this residual stress induced in the welded joints. Improper welding parameters input and clamping force will give rise to residual stress in the welded sheets. (b) Comment Fig 4. Caption may be "distance from the weld joint interface" It is understood that residual stress measurement was carried out in as welded condition before PWHT. The reasons for change of residual stresses with respect to magnitude and nature (tensile /compressive) from the weld interface to the base metal may be explained. Comparison of residual stresses pattern before and after PWHT may provide better understanding as the welded components usually are put in service after PWHT. This also helps in understanding the effect of PWHT in minimizing the residual stresses.
	Authors Response	The caption has been changed in Figure 5. The above comments have been addressed.
	Change in the manuscript	The residual stress is developed in the welded sheets due to non-uniform heat distribution. The welded region undergoes expansion, contraction of the molten pool and rapid cooling, which give rise to high residual stress of tensile in nature due to higher heat input. Tensile stresses in the material lead to the brittle fracture of the material. HAZ is affected during the welding due to exposure to the high temperature of the molten pool. whereas Base material experiences the least heat exposure and has minimal residual stress.

Sl. No.	Comments/ Responses/ Corrections	
		After post-weld heat treatment (PWHT) of IN718 welded joints, the residual stresses are reduced to compressive stresses by eliminating tensile stress. In the welded zone, the tensile stress of 507 MPa has been reduced to -152 MPa, as shown in Figure 5. It is observed all the tensile stress developed in and around the welded region has been reduced and converted to compressive stress, which will increase the strength of the material through this heat treatment cycle. This PWHT also has a significant role in increasing hardness as well as increasing the creep life of the sample. The maximum residual stress obtained in compressive stress is of -363 Mpa.
6	Reviewer comments	(a) paper ref.: IV. RESULTS AND DISCUSSION C. Creep behavior for IN718 TIG welded joints The creep behavior for IN718 TIG welded joints is studied for temperatures 550 °C and 650 °C, and stresses of 500 MPa and 700 MPa are carried out. (b) Comment · The Fig. 5(a) says the test temperature as 500 °C, does not match with the text (550 °C). It may be verified. · The title of the paper says the welded joints were characterized for creep behavior in presence of residual stresses but in the text it is silent. It may be stated that creep tests were performed before PWHT in as welded condition. · Comparison of creep performance of the weld joint before and after PWHT helps in quantifying the deleterious effect of the residual stresses.
	Authors Response	Fig.5 has been changed to Fig.6. The temperature has been verified and corrected in Fig.6. AS welded creep data is incorporated.
	Change in the manuscript	It is observed after the sample's PWHT creep life is increased and creep strain is lesser at higher stress levels in the range of 500 MPa. The formation of γ´ and γ´´ precipitates after PWHT increased the strength of the material, leading in increasing the life of the sample. Eliminating the residual stresses by PWHT also directly affects the creep life by enhancing the strength of the material due to compressive stresses.
7	Reviewer comments	General · The distortion in the welded joint both angular and planar may be measured and reported in the paper. · The nomenclature regarding welding process “GTAW” (or TIG) may be used throughout the paper for uniformity.
	Authors Response	TIG nomenclature has been incorporated throughout the paper.
	Change in the manuscript	The distortion in the welded joint is measured and represented in Figure 1 (b). The distortions are measured using weld gauges and represented in the coloured contour. It is observed both radial and angular distortions are measured, as shown in Figure 1 (b). The welded sheets are distorted more due to the welding of lengthier sheets of 210 mm length. Heat input and cooling time were higher, which gave rise to higher distortion levels.

Design, Modeling and Simulation of Deflector Plate For Flow Distribution in Combined Heat Exchanger for a Typical Fighter Aircraft

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Abstract - Design of components for any combat aircraft required to maintain size, weight and interfaces as per the system requirements. In thermal equipments, meeting pressure drop and thermal performance was a challenge for a given space envelop. In this paper, deflector plate with different configurations were designed and modeled for numerical analysis using ANSYS CFD fluent. CFD analysis has been carried out on combined condenser and Liquid Air heat exchanger using a deflector plate to study the mass flow distribution of cold air towards Condenser heat exchanger cold air circuit and Cold Air circuit of Liquid Air Heat Exchanger for distribution of required cold air flow & also to analyze the static pressure drop across combined heat exchanger so as to meet the design requirements. This paper also gives the details of the mass flow rate towards cold air circuits of Condenser and Liquid Air Heat Exchangers at different plate angles & for optimized hole patterns of deflector plate, CFD analysis for proposed configuration, results and discussions. The flow characteristics through combined heat exchanger under different deflector plate geometry, hole patterns & angles were studied using computational fluid dynamics technique. The flow field was visualized and the performance factors of combined heat exchanger with deflector plate were computed and compared against experimental data.

Keywords - Deflector plate, compact heat exchanger, Numerical analysis, fighter aircraft.

I. INTRODUCTION

The Environmental Control System (ECS) for a typical fighter aircraft is used for cabin cooling and pressurization, demisting operations, and avionics cooling. Presently most of the Fighter and Passenger Aircrafts Environmental Control System (ECS) are using conventional Bleed-Air Cycle System as ECS which consists of an Air Cycle Machine (ACM) along with a high-pressure water separator (HPWS). The Bleed-Air Cycle System uses the high pressure and high temperature bleed-air drawn from the compressor of the engine as a medium. This bleed air is cooled by passing through a series of compact heat exchangers and a Cold Air Unit (CAU). All the combat aircraft equipping with advanced Electronic warfare and Radar systems. These advanced electronic systems need thermal cooling for proper operation for the intended use. Cold air distribution is a challenge within the available space to meet the requirements. Combined Condenser Liquid Air Heat exchanger (CCLAHE) is a combination of two separate heat exchangers, namely the Condenser & the Liquid Air Heat Exchanger (LAHE), with their cores joined one above the other. Both heat exchangers share the same Cold Air stream coming from Turbine outlet of Cold Air Unit. The Condenser is a parallel flow heat exchanger, whereas the LAHE is a cross

counter flow heat exchanger. Both are of brazed aluminium plate & fin construction. Condenser cool the hot air coming from Reheater before it enters the Water Separator, by using the cold air coming from Turbine outlet while LAHE cool Ethylene Glycol coming from AESA Radar by using cold air coming from Turbine outlet. CFD analysis has been initiated on CCLAHE using a deflector plate to study the mass flow distribution of cold air towards Condenser & LAHE core for uniform distribution of flow & also to analyze the static pressure drop across CCLAHE unit so as to meet the design requirements. This report also gives the details of the mass flow rate towards Condenser & LAHE at different plate angles & for optimized hole patterns of deflector plate, effect of keeping plate on flow characteristics, CFD analysis for proposed configuration, results and discussions.

II. PROBLEM STATEMENT

For CCLAHE without deflector plate the static pressure drop across unit is high compared to the specified design value & also there is non-uniformity of flow in upper fin layers of Condenser. This high pressure drop & non uniform flow is creating a resistance to flow & resulting in performance irregularities. So, it is required to control & distribute the flow so as to keep pressure drop within specified limit & also to achieve the required mass flow distribution of air towards Condenser & LAHE cores. The flow rate can be controlled by using a deflector plate with holes so as to deflect the flow towards upper fin layers of condenser & to reduce the pressure drop.

The objective of the present work is to develop a CFD model of CCLAHE using the commercial code FLUENT, that accurately represents the flow-field and provides insight of three-dimensional behavior of the flow across CCLAHE and predicts the performance factors of the CCLAHE at different plate configuration and geometry.

III. CFDMODEL

CFD model gives the details of model geometry description, meshing, boundary conditions, meshing, meshing criteria, numerical method used.

A. Model Geometry Description

The computational model of CCLAHE & wireframe with deflector plate position is shown in fig 1. According to the Research of Huang and Kim the upstream and downstream pipe lengths should be at least 2 and 8 times disk diameters respectively. The downstream pipe lengths were extended to 15 times pipe diameter.

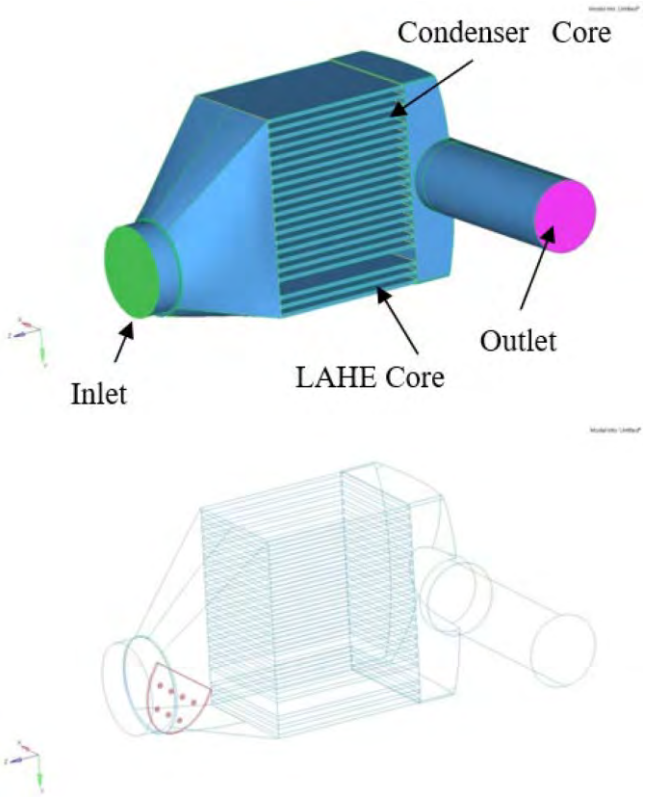

Fig 1. Computational domain

B. Meshing

Tetrahedral elements were used for meshing the model with prism layers for modeling boundary layer as shown in Figure 2, a grid independence study was conducted to ensure optimum grid size and grids were constructed for all CFD case studies of CCLAHE. The number of elements for each case was between 12,00000 and 15,00000 elements.

C. Boundary Conditions

The boundary conditions used for the analysis are tabulated in Table I, inlet mass flow rate was set at 0.55 kg/s, while the pressure at the outlet was 600 mbar 'g'. The plate surface & exterior surface were both set as wall with no-slip boundary condition

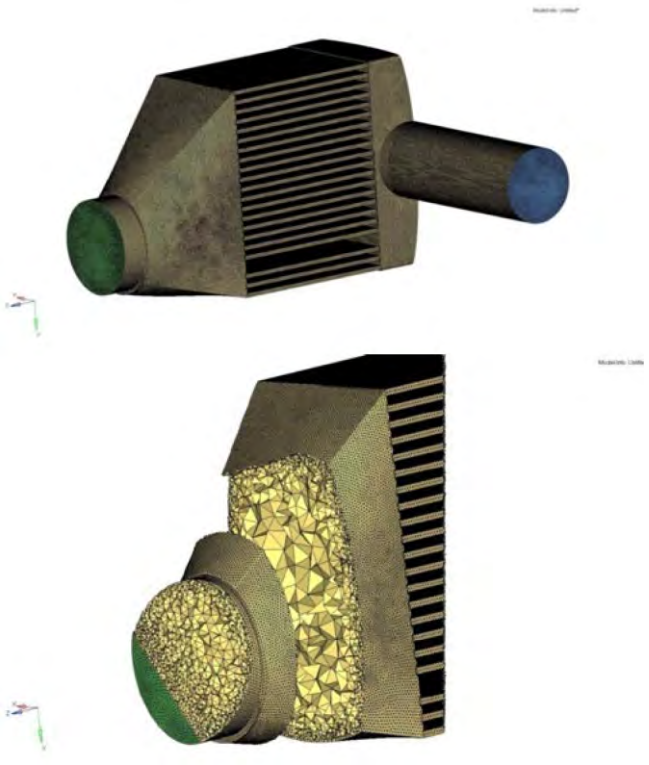

Fig 2. Generated mesh

while the inlet & outlet planes of Condenser & LAHE were treated as interior.

Table I
BOUNDARY CONDITIONS

Inlet	Mass Flow Rate
Condenser Inlet	Interior
LAHE Inlet	Interior
Condenser Outlet	Interior
LAHE Outlet	Interior
Default Exterior	Wall
Deflector Plate	Wall
Outlet	Pressure Outlet

D. Numerical method

Incompressible, Viscous, Turbulent flow was simulated through the CCLAHE cold air inlet by solving the Reynolds Averaged Navier-Stokes equations (RANS); its common form can be written as:

$$\rho\left[\frac{\partial \bar{V}}{\partial t} + (\bar{V}.\nabla)\bar{V}\right] = -\nabla P + \mu\nabla^2\bar{V} + \rho\bar{V}.\tau_{ij}$$

To deal with turbulence many models have been developed over the years. Two equation turbulence models have served as the foundation for much of the turbulence model research during the past two decades [20], they are the most commonly used in turbulent engineering problems due to robustness, lower computer requirements and relative accuracy. The Standard k-ε model which is a semi-empirical two equation model was chosen for this study. It relates the turbulent viscosity, the turbulent kinetic energy and the turbulent dissipation rate.

$$\frac{\partial}{\partial x_i}(\rho k\bar{u}_j) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\delta_k}\right)\frac{\partial k}{\partial x_i}\right] + \mu_t\left[\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right]\frac{\partial \bar{u}_i}{\partial x_i} - \rho\varepsilon$$

$$\frac{\partial}{\partial x_i}(\rho\varepsilon\bar{u}_j) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\delta_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{\varepsilon 1}\mu_t\left[\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right]\frac{\partial \bar{u}_i}{\partial x_i}\frac{\varepsilon}{k} - \rho C_{\varepsilon 2}\frac{\varepsilon^2}{k}$$

Where

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

and the empirical constants for the model are given in Table II

Table II
MODEL CONSTANTS

C_μ	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	δ_k	δ_ε
0.09	1.47	1.92	1	1.3

E. Convergence Criteria

Throughout the process of running the CFD software to solve the equations governed by the physics models selected, the residuals must be monitored for satisfactory convergence. Residuals represent the change in solution of each equation being solved after the each iteration. The following residuals were monitored by plotting the following after the every iteration: continuity, x-momentum, y-momentum, z-momentum, turbulent kinetic energy, and turbulent dissipation rate showing in Figure 3.

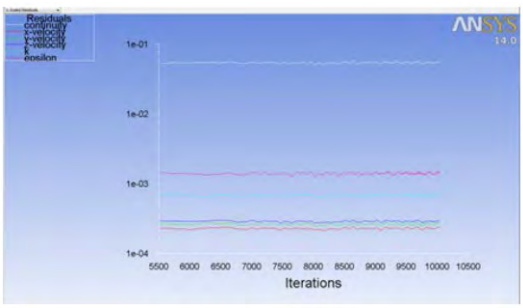

Fig. 3. Convergence Criteria

IV. RESULTS AND DISCUSSION

All the CFD simulations discussed were carried out using the criteria previously mentioned in section E. The flow fields generated by the simulations were studied, including visualizations of flow field streamlines, velocity vectors, and pressure fields. These visualizations are shown in Figure 1 to Figure 47 and shall be discussed accordingly.

A. Experimental Plate Case Study

2mm thick & 62mm length semi-circular plate kept at 11mm distance from inlet ferrule provided with 7 holes of 5mm diameter & inclined at 120° from axis of flow.

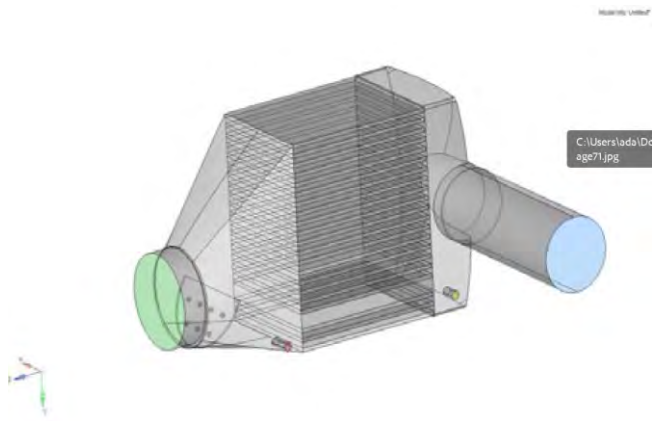

Fig. 4. Deflector Plate Position for BHEL Plate Case

1) Flow Field Description

With this deflector plate geometry and configuration, disturbance in flow field is observed. Flow contours shows turbulence & recirculation of velocity vectors in upper region & behind deflector plate in cold air inlet duct. Flow filed presents the path of movement of flow vectors, most of which are passing through Condenser core & LAHE core with significant velocity magnitude. Fluctuation in turbulent viscosity is observed during scaled residuals monitoring. Mass flow towards LAHE core is observed as 4.66 kg/min against the required 5.577 kg/min. The static pressure drop across CCLAHE unit between pressure tapping points at inlet & outlet header is observed as 100.88 mbar. The results for mass flow rate & static pressure drop are tabulated below:

Table III
MODEL CONSTANTS

	Condenser Core	LAHE Core
Mass Flow Rate (kg/min)	28.34	4.66
Pressure Drop (mbar)	100.88	

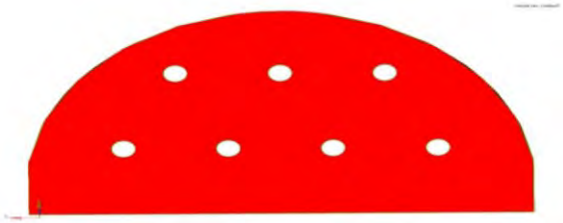

Fig. 5. Deflector Plate Configuration for BHEL Plate case

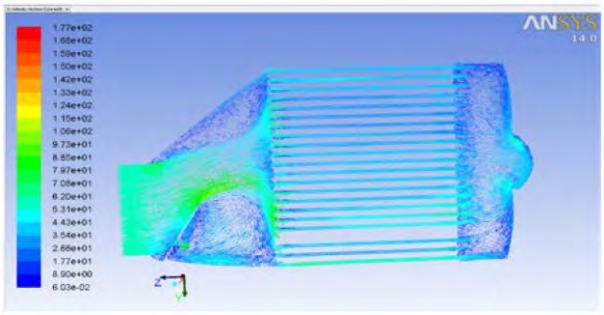

Fig. 6. Contours of Velocity Vectors for BHEL Plate Case

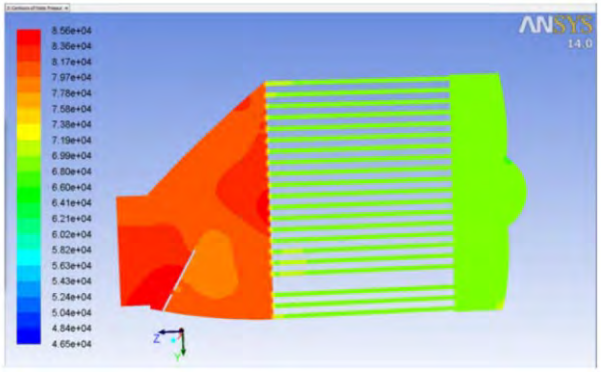

Fig. 7. Contours of Static Pressure for BHEL Plate Case

B. Case Study-1

2mm thick & 62mm length semi-circular plate kept at 11mm distance from inlet ferrule provided with 10 holes of 15mm diameter, 6 holes of 8mm diameter, 1 horizontal slot of 15mm diameter 51 mm in length & inclined at 120° from axis of flow.

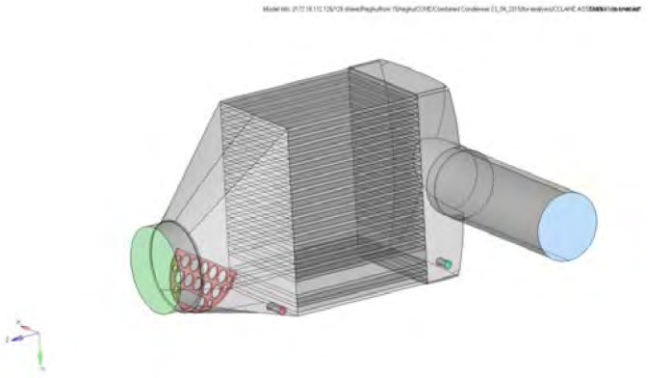

Fig. 8. Deflector Plate Position for Case Study-1

1) Flow Field Description

With this deflector plate geometry and configuration, disturbance in flow field is observed with increased pressure drop. Flow contours shows turbulence & recirculation of velocity vectors in upper region & behind deflector plate in inlet duct. Flow filed presents the path of movement of flow vectors, most of which are passing through Condenser core & LAHE core with significant velocity magnitude. Fluctuation in turbulent viscosity is observed during scaled residuals monitoring. Mass flow towards LAHE core is observed as 5.20 kg/min against the required 5.577 kg/min. The static pressure drop across CCLAHE unit between pressure tapping points at inlet & outlet header is observed as 116.89 mbar. The results for mass flow rate & static pressure drop are tabulated below:

Table IV
RESULT FOR CASE STUDY-1

	Condenser Core	LAHE Core
Mass Flow Rate (kg/min)	27.80	5.20
Pressure Drop (mbar)	116.89	

Fig. 9. Deflector Plate Configuration for Case Study-1

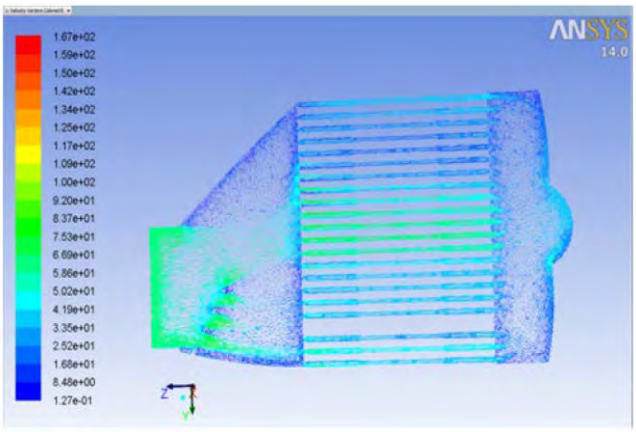

Fig. 10. Contours of Velocity Vectors for Case Study-1

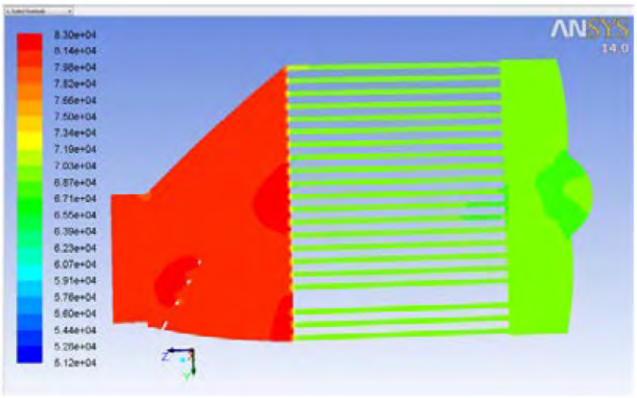

Fig. 11. Contours of Static Pressure for Case Study-1

C. Case Study-2

2mm thick & 62mm length semicircular plate kept at 11mm distance from inlet ferrule provided with 7 holes of 15mm diameter, 6 holes of 8mm diameter, 2 horizontal slot of 15mm diameter 51 mm in length & inclined at 120° from axis of flow.

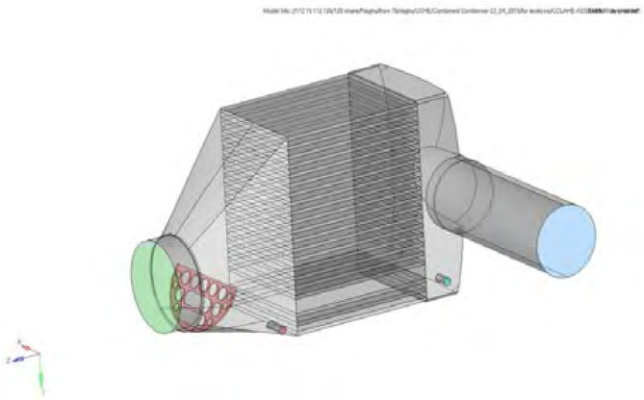

Fig. 12. Deflector Plate Position for Case Study-2

1) Flow Field Description

With this deflector plate geometry and configuration disturbance in flow field is observed with increased pressure drop. Flow contours shows turbulence & recirculation of velocity vectors in upper region & behind deflector plate in inlet duct. Flow filed presents the path of movement of flow vectors, most of which are passing through Condenser core & LAHE core with significant velocity magnitude. Fluctuation in turbulent viscosity is observed during scaled residuals monitoring. Mass flow towards LAHE core is observed as 5.21 kg/min against the required 5.577 kg/min. The static pressure drop across CCLAHE unit between pressure tapping points at inlet & outlet header is observed as 116.79 mbar. The results for mass flow rate & static pressure drop are tabulated below:

Table V
RESULT FOR CASE STUDY-2

	Condenser Core	LAHE Core
Mass Flow Rate (kg/min)	27.79	5.21
Pressure Drop (mbar)	116.79	

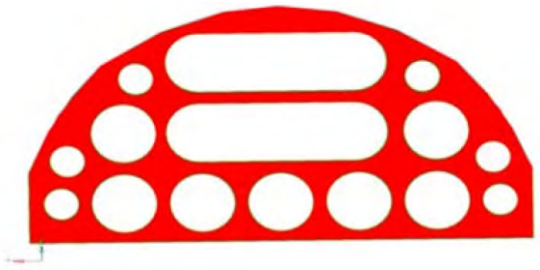

Fig. 13. Deflector Plate Position for Case Study-2

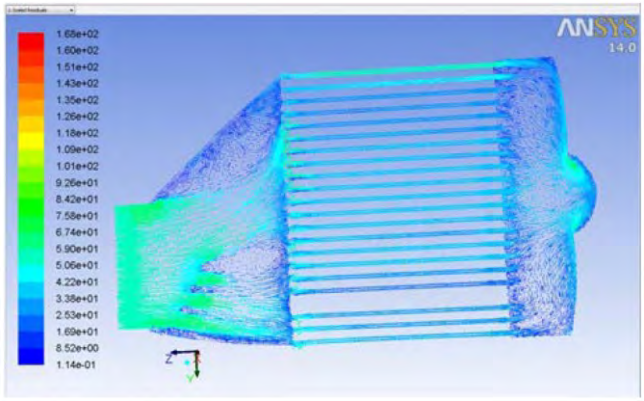

Fig. 14. Contours of Velocity Vectors for Case Study-2

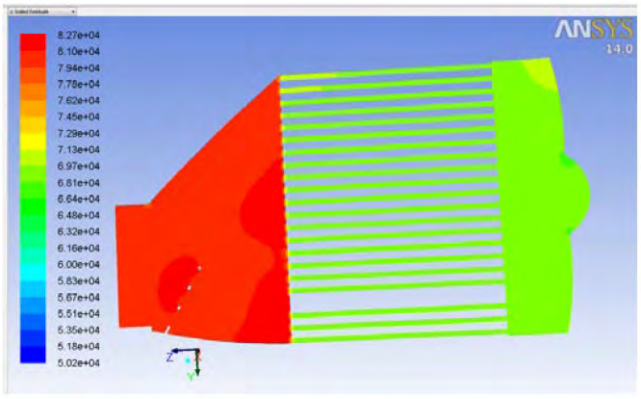

Fig. 15. Contours of Static Pressure for Case Study-2

D. Case Study-3

2mm thick & 62mm length semicircular plate kept at 11mm distance from inlet ferrule provided with 5 holes of 15mm diameter, 6 holes of 8mm diameter, 2 horizontal slot of 15mm diameter 51 mm & 87mm in length & inclined at 135° from axis of flow.

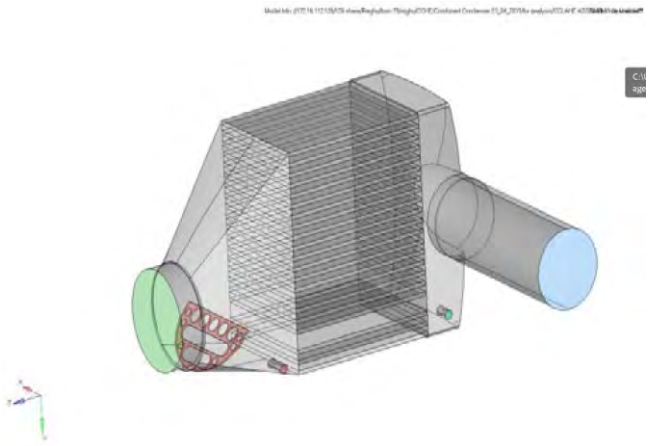

Fig. 16. Deflector Plate Position for Case Study-3

1) Flow Field Description

With this deflector plate geometry and configuration disturbance in flow field is observed with increased pressure drop. Flow contours shows turbulence & recirculation of velocity vectors in upper region & behind deflector plate in inlet duct. Flow filed presents the path of movement of flow vectors, most of which are passing through Condenser core & LAHE core with significant velocity magnitude. Fluctuation in turbulent viscosity is observed during scaled residuals monitoring. Mass flow towards LAHE core is observed as 5.26 kg/min against the required 5.577

kg/min. The static pressure drop across CCLAHE unit between pressure tapping points at inlet & outlet header is observed as 119.81 mbar. The results for mass flow rate & static pressure drop are tabulated below:

Table VI
RESULT FOR CASE STUDY-3

	Condenser Core	LAHE Core
Mass Flow Rate (kg/min)	27.74	5.26
Pressure Drop (mbar)	119.81	

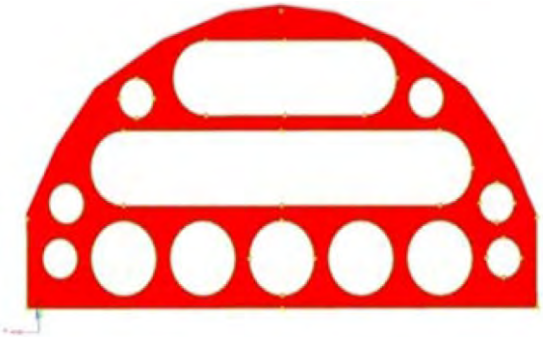

Fig. 17. Deflector Plate Configuration for Case Study-3

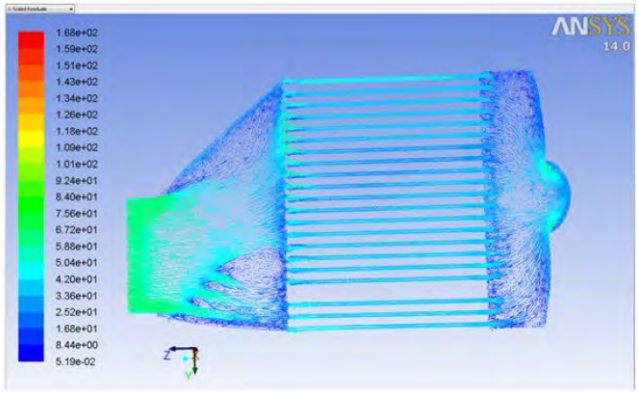

Fig. 18. Contours of Velocity Vectors for Case Study-3

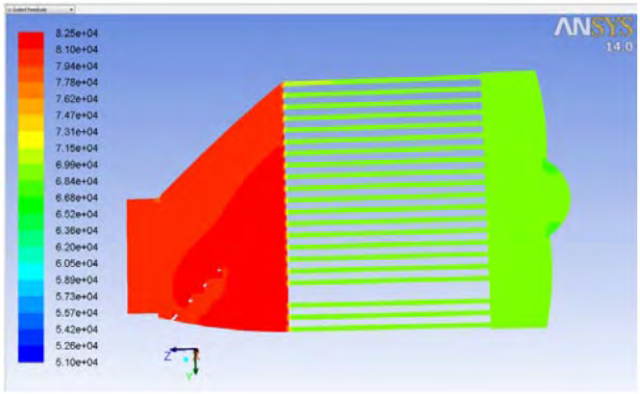

Fig. 19. Contours of Static Pressure for Case Study-3

E. Case Study-4

2mm thick & 62mm length semicircular plate kept at 11mm distance from inlet ferrule provided with 4 holes of 8mm diameter, 3 horizontal slots of 15mm diameter 51 mm in length & 2 vertical slots of 15mm diameter 33mm in length inclined at 120° from axis of flow.

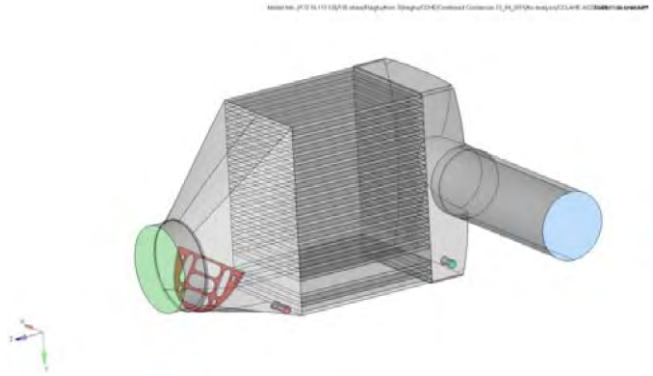

Fig. 20. Deflector Plate Position for Case Study-4

1) Flow Field Description

With this deflector plate geometry and configuration, disturbance in flow field is observed with increased pressure drop. Flow contours shows turbulence & recirculation of velocity vectors in upper region & behind deflector plate in inlet duct. Flow filed presents the path of movement of flow vectors, most of which are passing through Condenser core & LAHE core with significant velocity magnitude. Fluctuation in turbulent viscosity is observed during scaled residuals monitoring. Mass flow towards LAHE core is observed as 5.17 kg/min against the required 5.577 kg/min. The static pressure drop across CCLAHE unit between pressure tapping points at inlet & outlet header is observed as 118.12 mbar. The results for mass flow rate & static pressure drop are tabulated below:

Table VII
RESULT FOR CASE STUDY-4

	Condenser Core	LAHE Core
Mass Flow Rate (kg/min)	27.83	5.17
Pressure Drop (mbar)	118.12	

Fig. 21. Deflector Plate Configuration for Case Study-4

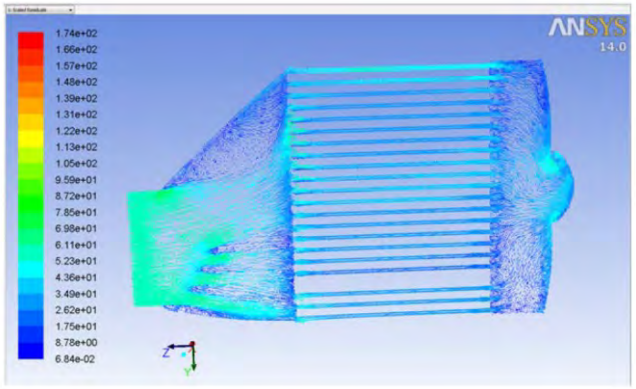

Fig. 22. Contours of Velocity Vectors for Case Study-4

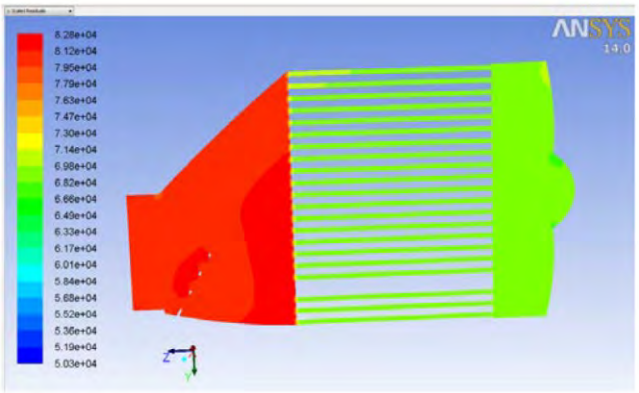

Fig. 23. Contours of Static Pressure for Case Study-4

F. Case Study-5

2mm thick & 40mm length semicircular plate kept at 11mm distance from inlet ferrule provided with 8 holes of 15mm diameter, 2 holes of 5mm diameter & inclined at 135° from axis of flow.

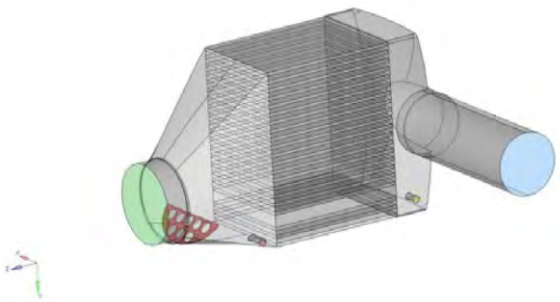

Fig. 24. Deflector Plate Position for Case Study-5

1) Flow Field Description

With this deflector plate geometry and configuration disturbance in flow field is observed with increased pressure drop. Flow contours shows turbulence & recirculation of velocity vectors in upper region & behind deflector plate in inlet duct. Flow filed presents the path of movement of flow vectors, most of which are passing through Condenser core & LAHE core with significant velocity magnitude. Fluctuation in turbulent viscosity is observed during scaled residuals monitoring. Mass flow towards LAHE core is observed as 5.15 kg/min against the required 5.577 kg/min. The static pressure drop across CCLAHE unit between pressure tapping points at inlet & outlet header is observed as 118.18 mbar. The results for mass flow rate & static pressure drop are tabulated below:

Table VIII
RESULT FOR CASE STUDY-5

	Condenser Core	LAHE Core
Mass Flow Rate (kg/min)	27.85	5.15
Pressure Drop (mbar)	118.18	

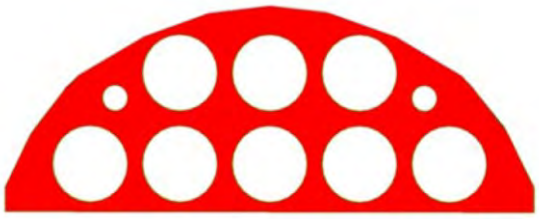

Fig. 25. Deflector Plate Configuration for Case Study-5

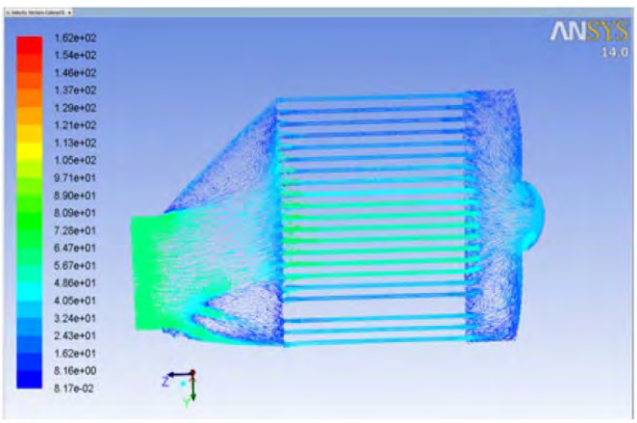

Fig. 26. Contours of Velocity Vectors for Case Study-5

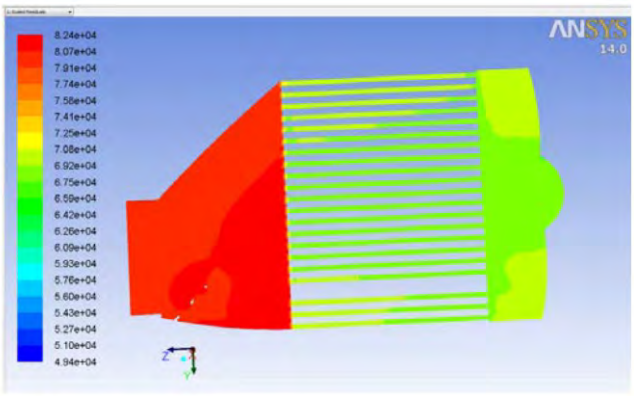

Fig. 27. Contours of Static Pressure for Case Study-5

G. Case Study-6

2mm thick & 41mm length semicircular plate kept at 11mm distance from inlet ferrule provided with 2 holes of 10mm diameter, 2 horizontal slots of 15mm ,12mm diameter & 51 mm & 96mm in length & inclined at 135° from axis of flow.

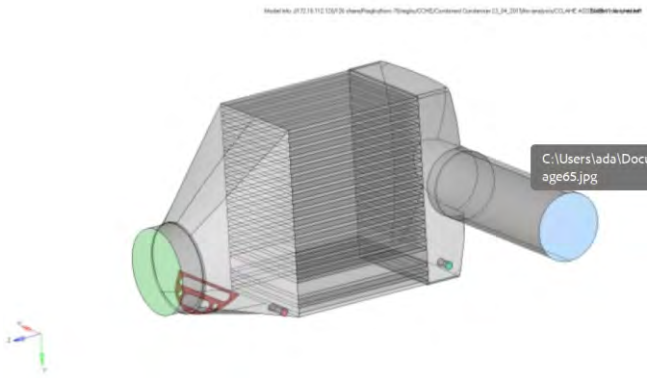

Fig. 28. Deflector Plate Position for Case Study-6

1) Flow Field Description

With this deflector plate geometry and configuration disturbance in flow field is observed with increased pressure drop. Flow contours shows turbulence & recirculation of velocity vectors in upper region & behind deflector plate in inlet duct. Flow filed presents the path of movement of flow vectors, most of which are passing through Condenser core & LAHE core with significant velocity magnitude. Fluctuation in turbulent viscosity is observed during scaled residuals monitoring. Mass flow towards LAHE core is observed as 5.17 kg/min against the required 5.577 kg/min. The static pressure drop across CCLAHE unit between pressure tapping points at inlet & outlet header is observed as 119.49 mbar. The results for mass flow rate & static pressure drop are tabulated below:

Table IX
RESULT FOR CASE STUDY-6

	Condenser Core	LAHE Core
Mass Flow Rate (kg/min)	27.83	5.17
Pressure Drop (mbar)	119.49	

Fig. 29. Deflector Plate Configuration for Case Study-6

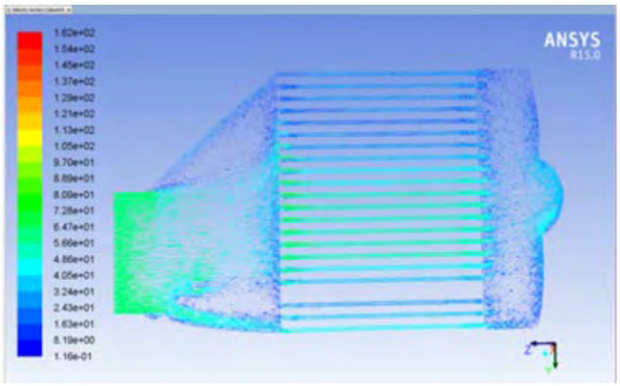

Fig. 30. Contours of Velocity Vectors for Case Study-6

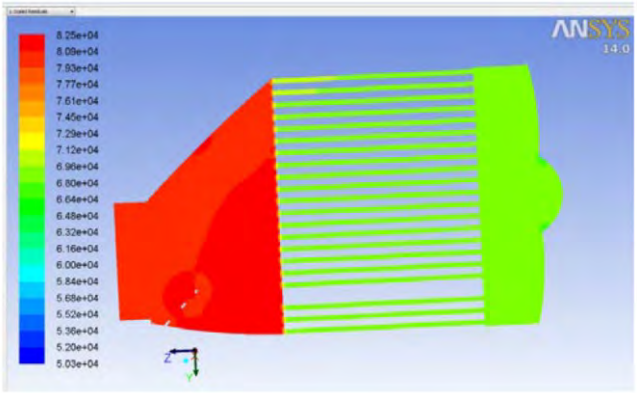

Fig. 31. Contours of Static Pressure for Case Study-6

H. Case Study-7

2mm thick & 38.5mm length plate kept at 11mm distance from inlet ferrule provided with 5 holes of 15mm diameter, 4 holes of 8mm diameter, 1 horizontal slot of 15mm diameter 87mm in length & inclined at 135° from axis of flow.

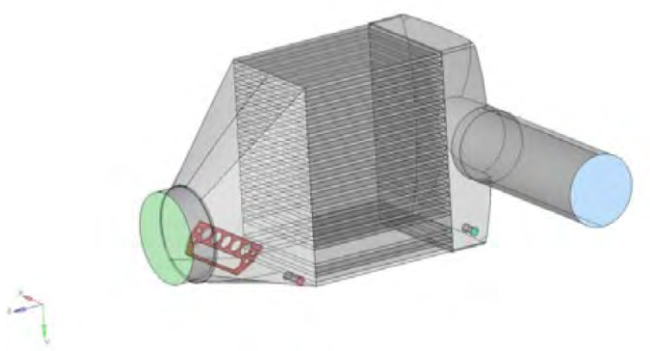

Fig. 32. Deflector Plate Position for Case Study-7

1) Flow Field Description

With this deflector plate geometry and configuration disturbance in flow field is observed with increased pressure drop. Flow contours shows turbulence & recirculation of velocity vectors in upper region & behind deflector plate in inlet duct. Flow filed presents the path of movement of flow vectors, most of which are passing through Condenser core & LAHE core with significant velocity magnitude. Fluctuation in turbulent viscosity is observed during scaled residuals monitoring. Mass flow towards LAHE core is observed as 5.27 kg/min against the required 5.577 kg/min. The static pressure drop across CCLAHE unit between pressure tapping points at inlet & outlet header is observed as 118.89 mbar. The results for mass flow rate & static pressure drop are tabulated below:

Table X
RESULT FOR CASE STUDY-7

	Condenser Core	LAHE Core
Mass Flow Rate (kg/min)	27.73	5.27
Pressure Drop (mbar)	118.89	

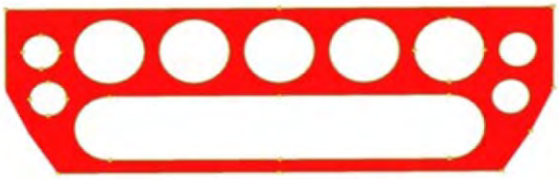

Fig. 33. Deflector Plate Configuration for Case Study-7

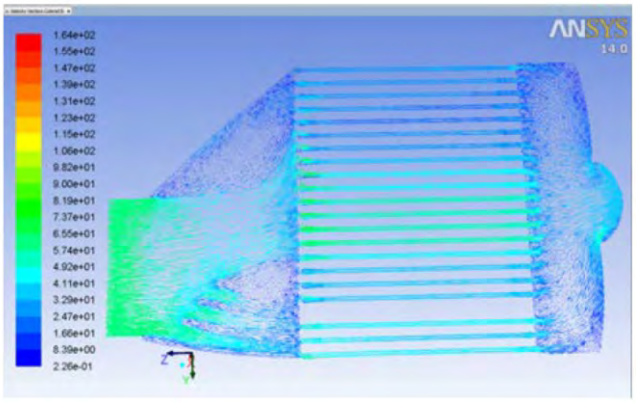

Fig. 34. Contours of Velocity Vectors for Case Study-7

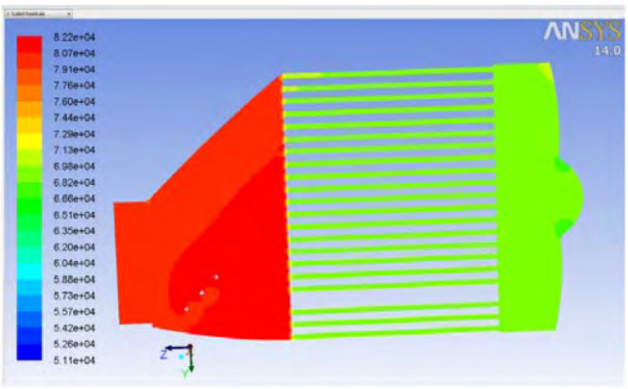

Fig. 35. Contours of Static pressure for Case Study-7

I. Case Study-8

2.29 mm thick &110 mm length plate kept at 43 mm distance from inlet ferrule provided with 19 holes of 6mm diameter & 3 holes of 8 mm diameter inclined at 1200 from the axis of flow.

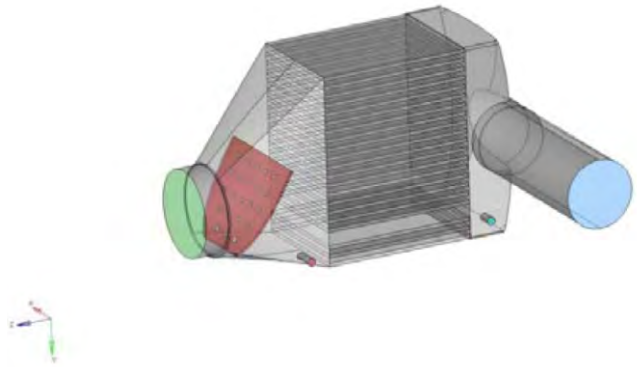

Fig. 36. Deflector Plate Position for Case Study-8

1) Flow Field Description

With this deflector plate geometry and configuration disturbance in flow field is significantly reduced & also improvement over pressure drop is observed. Flow contours show significant reduc-

tion in turbulence & recirculation of velocity vectors in upper region & behind deflector plate in inlet duct. Flow filed presents the improvement over flow non uniformity towards Condenser & LAHE cores. Frequent fluctuation in turbulent viscosity is also reduced during scaled residuals monitoring. Mass flow towards LAHE core is observed to be 5.15 kg/min against the required 5.577 kg/min. The static pressure drop across CCLAHE unit is observed as 95.11 mbar. The results for mass flow rate & static pressure drop are tabulated below:

Table XI
RESULT FOR CASE STUDY-8

	Condenser Core	LAHE Core
Mass Flow Rate (kg/min)	27.85	5.15
Pressure Drop (mbar)	95.11	

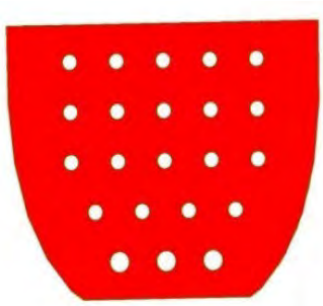

Fig. 37. Deflector Plate Configuration for Case Study-8

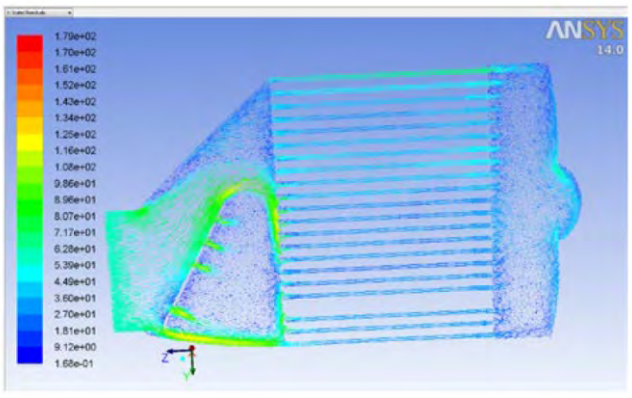

Fig. 38. Contours of Velocity Vectors for Case Study-8

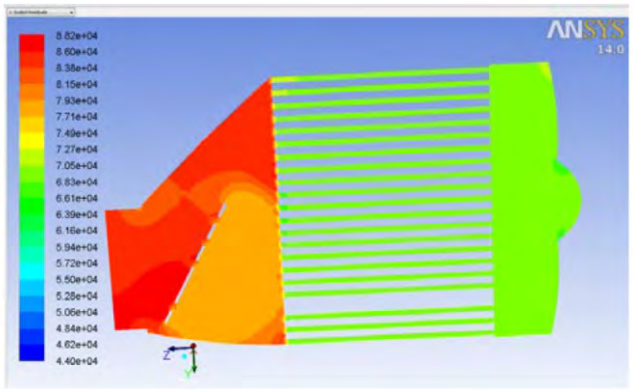

Fig. 39. Contours of Static pressure for Case Study-8

J. Case Study-9

2.29 mm thick & 110 mm length plate kept at 43 mm distance from inlet ferrule provided with 19 holes of 8 mm diameter & 3 holes of 10 mm diameter inclined at 1200 from axis of flow.

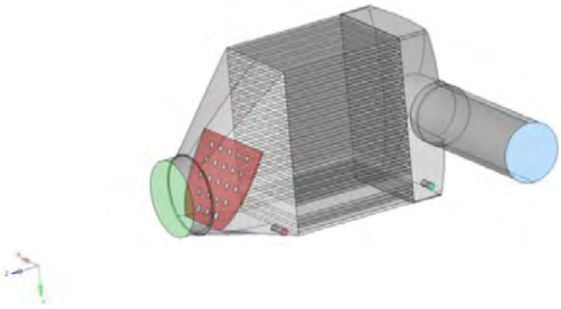

Fig. 40. Deflector Plate Position for Case Study-9

1) Flow Field Description

With this deflector plate geometry and configuration disturbance in flow field is increased from previous case study& also increase over pressure drop is observed. Flow contours show slight increase in turbulence & recirculation of velocity vectors in upper region & behind deflector plate in inlet duct. Flow filed presents the improvement over flow non uniformity towards Condenser & LAHE cores. Frequent fluctuation in turbulent viscosity is also reduced during scaled residuals monitoring. Mass flow towards LAHE core is observed to be 5.32 kg/min against the required 5.577 kg/min. The static pressure drop across CCLAHE unit is observed as 99.20 mbar. The results for mass flow rate & static pressure drop are tabulated below:

Table XII
RESULT FOR CASE STUDY-9

	Condenser Core	LAHE Core
Mass Flow Rate (kg/min)	27.68	5.32
Pressure Drop (mbar)	99.20	

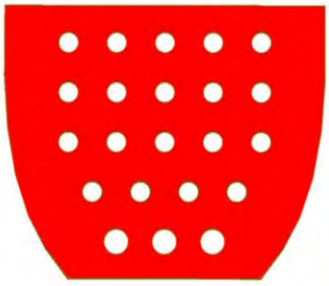

Fig. 41. Deflector Plate Configuration for Case Study-9

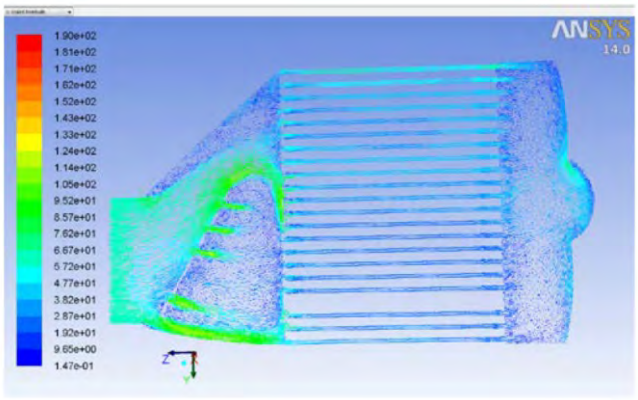

Fig. 41. Deflector Plate Configuration for Case Study-9

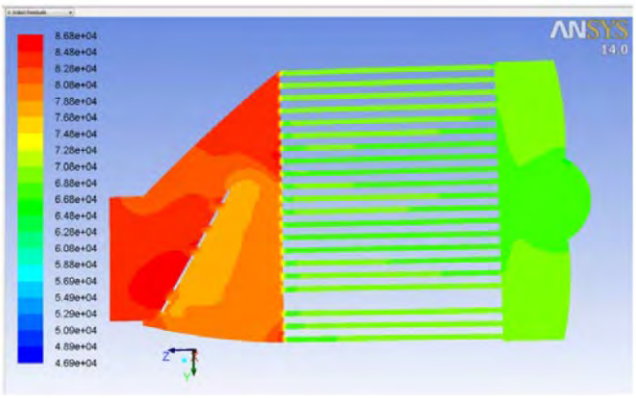

Fig. 41. Deflector Plate Configuration for Case Study-9

K. Case Study-10

2.29 mm thick & 110 mm length plate kept at 43 mm distance from inlet ferrule provided with 15 holes of 6 mm diameter & 4 holes of 8 mm diameter & 3 holes of 12.5 mm diameter, kept at height of 8.64 mm, inclined at 1200 from axis of flow

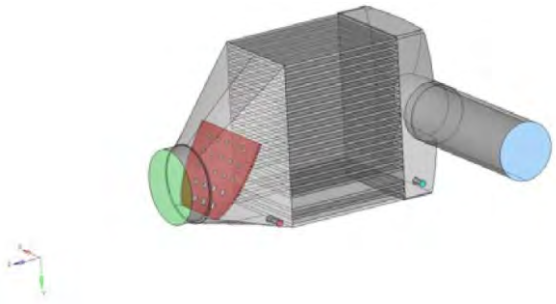

Fig. 44. Deflector Plate Position for Case Study-10

1) Flow Field Description

With this deflector plate geometry and configuration disturbance in flow field is significantly reduced & also improvement over pressure drop is observed. Flow contours show significant reduction in turbulence & recirculation of velocity vectors in upper region & behind deflector plate in inlet duct. Flow filed presents the improvement over flow non uniformity towards Condenser & LAHE cores. Frequent fluctuation in turbulent viscosity is also reduced during scaled residuals monitoring. Mass flow towards LAHE core is observed to be 5.97 kg/min against the required 5.577 kg/min. The static pressure drop across CCLAHE unit is observed as 96.14 mbar. The results for mass flow rate & static pressure drop are tabulated below:

Table XIII
RESULT FOR CASE STUDY-10

	Condenser Core	LAHE Core
Mass Flow Rate (kg/min)	27.03	5.97
Pressure Drop (mbar)	96.14	

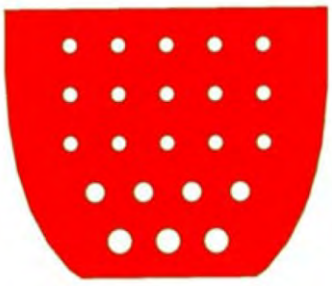

Fig. 45. Deflector Plate Configuration for Case Study-10

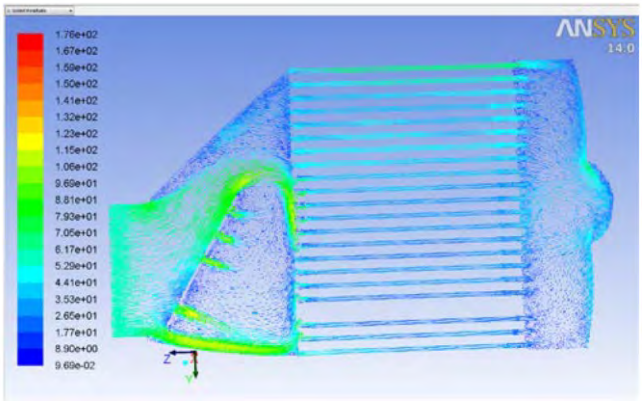

Fig. 46. Contours of Velocity Vectors for Case Study-10

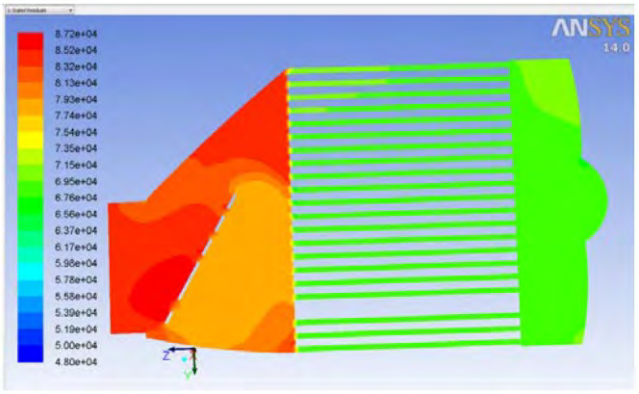

Fig. 47. Contours of Static pressure for Case Study-10

L. Comparison of Numerical Results with Experimental Data

These results are indicated that the pressure drop across the CCLAHE unit is changing with change in hole diameter and number of holes as well as with deflector plate inclination with flow axis. The comparison for static pressure drop is tabulated below:

Table XIV
PRESSURE DROP ACROSS CCLAHE UNIT

Case Study	Pressure drop (mbar)	
	Numerical	Experimental
BHEL Case	100.88	101.1
1	116.89	113.1
2	116.79	-
3	119.81	-
4	118.12	-
5	118.18	-
6	119.49	-
7	118.89	115.1
8	95.11	93.2
9	99.20	97.6
10	96.14	89.3

The numerically predicted data is close to the experimental data with some tolerance. Case studies 8, 9 & 10 were found to be significant for reduction in pressure drop as well as improvement over mass flow rates towards Condenser & LAHE cores.

M. Effect of pressure drop across CCLAHE unit on Mass Flow rate

The mass flow rate of cold air coming out from Turbine outlet of CAU towards Condenser & LAHE cores is tabulated below for each CFD case study.

Table XV
EFFECT OF PRESSURE DROP ON MASS FLOW RATE

Case Study	Pressure drop (mbar)		Mass Flow Rate (kg/min)	
	Numerical	Experimental	Condenser	LAHE
BHEL Case	100.88	101.1	28.34	4.66
1	116.89	113.1	27.80	5.20
2	116.79	–	27.79	5.21
3	119.81	–	27.74	5.26
4	118.12	–	27.83	5.17
5	118.18	–	27.85	5.15
6	119.49	–	27.83	5.17
7	118.89	115.1	27.73	5.27
8	95.11	93.2	27.85	5.15
9	99.20	97.6	27.68	5.32
10	96.14	89.3	27.03	5.97

It is observed for each CFD case study that mass Flow Rate of cold air towards LAHE core is changing while Pressure Drop across CCLAHE unit is reducing and also with increase in mass flow towards LAHE, Flow non uniformity is also getting reduced as resistance to flow is reducing.

V. CONCLUSION

The flow characteristics through CCLAHE under different deflector plate geometry, hole patterns & angles were studied using computational fluid dynamics technique. The flow field was visualized and the performance factors of CCLAHE with deflector plate were computed and compared against experimental data. Based on the CFD analysis and comparison with experimental data the following conclusions are made.

- The CFD Predicted values are validated with experimental data for CCLAHE with deflector plate for required pressure drop & mass flow respectively. The CFD model was validated.
- The pressure drop across the CCLAHE unit and flow rates were directly dependent on the angular position of deflector plate with flow axis and hole patterns. As the plate angle increases from 120° to 135°mass flow towards LAHE is changing and static pressure drop is also changing with optimized holes & slots.
- Case Studies 8, 9 & 10 found to be significant for analysis of required pressure drop & mass flow requirements across Condenser & LAHE cores.
- The CFD estimated deflector plate angle for meeting the required mass flow rate of 27.423 kg/min& 5.577 kg/min towards Condenser & LAHE cores is 1200 with optimized hole patterns of case study-10. The Pressure drop values are compared with the theoretical estimated value for some CFD case studies. The CFD estimated values and theoretical calculated values are close to each other with some error tolerance.
- Case study -10 is recommended to use in the CCLAHE cold air inlet duct side as a flow deflector plate, which meets the cold air circuit flow and pressure drop requirements.

VI. ACKNOWLEDGEMENTS

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[1]

Development of eco-friendly Zn-Ni plating on Low alloy high strength steel parts, as an alternative to Cadmium plating, for aircraft applications.

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Abstract - The article presents the experimental research studies on development of Zn-Ni plating process on high strength low alloy Ni-Cr-Mo steel as alternative to presently used cadmium plating process on aircraft steel parts. Usually, aircraft steel parts made of high strength low alloy Ni-Cr-Mo steel, are protected from corrosion by applying cadmium plating. Cadmium plating has an excellent corrosion resistance and offers sacrificial protection to steel without compromising on mechanical properties of the substrate metal while maintaining lubricity [1]. Inspite of sevaral advantages, cadmium plating is being phased out because of its inherent toxicity, environmental hazards and associated regulations [2,3]. The Zn-Ni plating provides sacrificial protection to steel parts without affecting the base metal mechanical properties while maintaining the environmental compatibility. Zn-Ni protection also offers improved corrosion resistance over cadmium plating with comparable lubricity. In the present investigation, the process is briefly explained and the results of different characterization of the plated specimens are reported.

Keywords - Zn-Ni, Corrosion, lubricity, cadmium plating

I. INTRODUCTION

Cadmium (Cd) electrochemistry coatings have many uses because they have good corrosion resistance in saline environment, have low friction coefficient and make a fair electrical contact. Cadmium coatings are used mostly in components for the electrical, electronic, communications, automotive, aeronautic and locks industries.[5]. Cd plating is applied by electroplating process followed by chromate, Cr6+ conversion coating. Due to the toxic nature of cadmium and carcinogenic nature of Cr6+, there is a need for an ecofriendly replacement [1]. Cadmium plating is forbidden under the European RoHS, ELV and WEEE rules and restricted under REACH. Currently, efforts are being made to find a suitable alternative. Zinc (Zn) based coatings have the potential for use as a corrosion-resistant barrier. Zinc alloys will retain their sacrificial property by anodic behavior to steel, but at lower corrosion rate thereby increasing the corrosion resistance of

steel. Iron group metals (Fe, Ni, Co), nobler than zinc help to increase the electrode potential and subsequently the corrosion resistance. Zn-Ni, Zn-Fe, Zn-Co, Zn-Ni-Co, Zn-Ni-Fe have been considered as possible solutions. Among all, Zn-Ni showed superior corrosion resistance compared to pure Zn because of formation of several complex products which act as barrier to the corrosion environment protecting the underlying coating. Also, it imparts comparable good mechanical properties, superior formability and improved welding characteristics [6-7]. The present work contents optimization of Zn-Ni plating and its characterization in production scale of 500 liter bath catering the need of aircraft components. During scaling up of the process several problems were faced, which were eliminated one by one and finally achieved quality of the coating. Followed by successful qualification testing, the approval of the process was obtained by airworthiness agencies.

In this work, Zn–Ni coatings have been deposited on a high strength Ni-Cr-Mo steel, SAE 4340 with an Ni content of about 10-16 wt%, by using near neutral bath. The coatings have been evaluated for several qualification tests such as coating thickness, adhesion, coating uniformity, surface morphology, lubricity, wear resistance test, corrosion by salt spray test, tensile, fatigue, hardness and hydrogen embrittlement test as per the test matrix.

II. EXPERIMENTAL

2.1. Electrolyte preparation and deposition:

The standard bath compositions and deposition conditions for Zn-Ni deposits are given in Table 1. The solutions were prepared using distilled water and reagent grade chemicals. The NCM steel (SAE 4340) was used as a substrate. Chemical composition and mechanical properties of substrate are given below in Table 2

Table 1: Zn-Ni bath composition and parameters

Chemicals/Reagents	Composition
Potassium Chloride	180-240 g/L
Zinc Chloride	34-76 g/L
Nickel Chloride hexahydrate	92-128 g/L
Current Density	160 mA/inch2
pH	5.2-5.6
Temperature	30-45°C

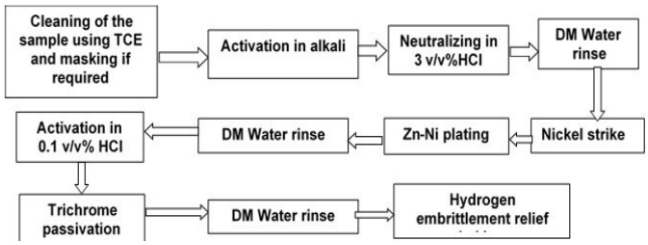
Table 2: Substrate NCM Steel (SAE 4340) Composition in Wt.% by EDX of NCM steel and mechanical properties in hardened and tempered condition tested as per ASTM E8.

	%C	Ni	Cr	Mn	Si	Mo	Fe
Required	0.36/ 0.44	2.3/ 2.8	0.5/ 0.8	0.45/ 0.70	0.10 /0.35	0.45 /0.65	Bal.
Obtained	0.41	2.4/ 2.6	0.75 /0.8	0.67 /1.0	0.52/ 0.55	0.42/ 0.58	94.4/ 95.1

	UTS (Mpa) Min.	YS (MPa) Min.	%El Min	Hardness
Mech. Prop. Required.	1230-1420	1080	10%	363/415 HBW
Obtained	1248	1174	14%	370 HBW

For 500 liter production scale bath to maintain the bath stability and uniformity in coating, various additives were added. Anode to Cathode surface area ratio was maintained as 1:2 to 2:1. Cathode rod movement which was essential for covering surface area of substrate and maintaining coating uniformity was considered as 3-5 m/min.

Table 3: Plating operation sequence



Initially, the experiments were carried out by using 40 liter plating bath before scaling up to production level. The bath set up is given in fig.1.

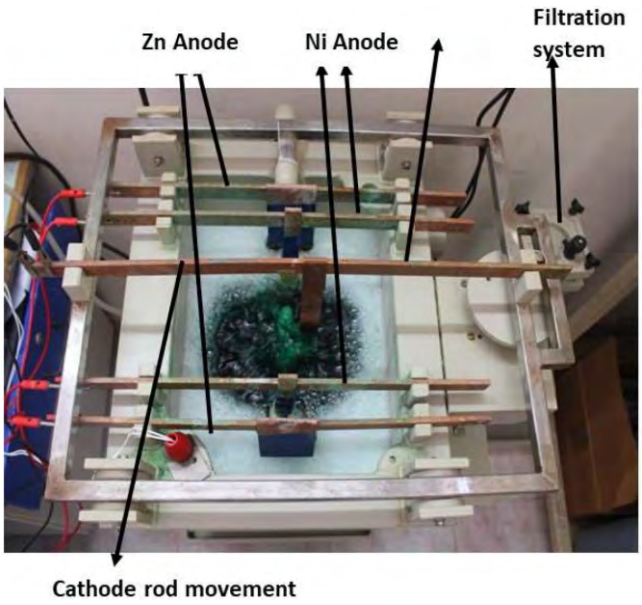


Fig. 1: 40 liter Zn-Ni plating bath operational set up.

The plating operational sequence was followed as mentioned in Table 3. NCM steel (SAE 4340) disc was used as substrate for plating [Fig. 2]. After plating the plated disc was tested for adhesion, plating composition and thickness and found satisfactory.

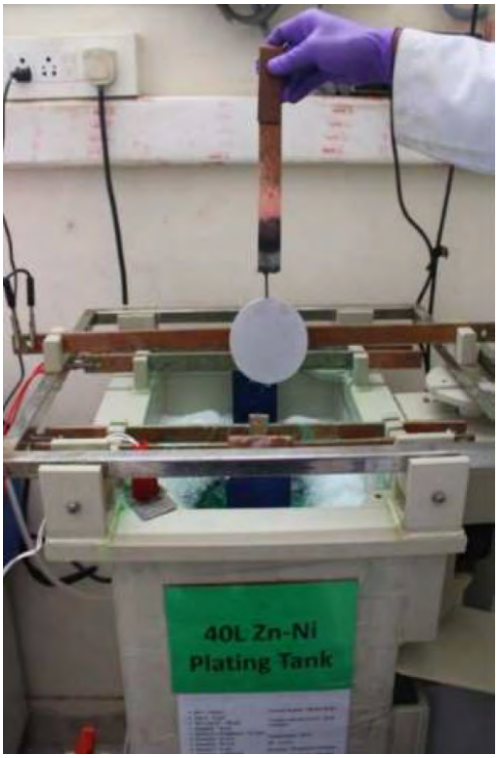


Fig. 2: NCM steel disc Zn-Ni plated in 40 liter bath.

A Type test schedule was prepared [8], which contents the elaborated testing details along with specifications and acceptance criteria. One qualification test batch was carried out and tested. The qualification tests such as adhesion, plating composition, plating thickness & uniformity, corrosion by salt spray test, tensile, hardness, fatigue, lubricity & wear resistance and hydrogen embrittlement were completed and found satisfactory. The Qualification test matrix is given in Table 4.

Table 4: Qualification Test matrix details

Sl. No.	Tests	Standard	Requirements
1.	Chemical Composition	AMS 2417J	Ni content 10-16 wt% Bal. Zn
2.	Microstructure	-	-
3.	Plating thickness	AMS 2417J	10-15 microns
4.	Adhesion test Cross-hatch test Band test	ASTM D3359 – ASTM B571	No blisters, delamination, peeling of the coating observed
5.	Hardness	ASTM E384	400 ± 35 VHN
6.	Wear Resistance	ASTM G133	Total height loss 10±3 µm
7.	Lubricity Test (Coefficient of friction)	ASTM G133	Coefficient of frication: 0.10 ± 0.03
8.	Salt (fog) Spray Corrosion Resistance	ASTM B117 & AMS 2417J	No white rust for 96 h and no red rust formation for 500 h
9.	Tensile Test	HPS 901, Type D, Size 4/ ASTM E8	As per Table 2.
10.	Fatigue Test	LTP 147 Stress: 600 MPa, Kt= 1.0, R= -1, 1 Lakh cycles	No fracture, coating delamination after 1 lakh cycles
11.	Hydrogen embrittlement test	ASTM F519 (Type 1a.1)	Shall pass min.200 hrs

After successful trials and optimization of bath parameters in 40 liters, it was decided to perform plating in 500 liters bath. The same chemicals were used and scaled up to the required level. NCM

substrate samples were used and several batches were made suiting to anode-cathode ratio. The important steps followed as below:

a) Degreasing and Mild alkali treatment: The NCM steel disc along with test samples were initially degreased with TCE followed by mild alkali treatment. The composition of mild alkali bath and the process parameters adopted are given Table 4.

Table 4: Mild Alkali treatment details:

NaOH	8 - 10 g/L
Na2CO3	15 - 20 g/L
Na2HPO4	12 - 15 g/L
Current Density	160 ± 5 mA/inch2
Temperature	80°C
Time	5 minutes

b) Neutralizing in acid: The treated disc and test samples were rinsed thoroughly with distilled water followed by neutralizing by immersion in 3 v/v% HCl for 30 secs.

c) Nickel strike: Nickel strike was given to obtain an adherent Zn-Ni plating on NCM steel. The neutralized disc and test samples were rinsed in distilled water followed by nickel strike was given. The bath composition and the process parameters are given in Table 5.

Table 5: Nickel strike details:

NiCl2.6H2O	300 - 325 g/L
HCL	125 – 130 ml/L
Current density	100 mA/inch2
Temperature	Ambient condition
Time	4 minutes

d) Zn-Ni plating: After Nickel strike, followed by rinsing in Distilled water immediately the disc & samples were transferred to Zn-Ni plating bath. The plating parameters and bath details are given in Table 1.

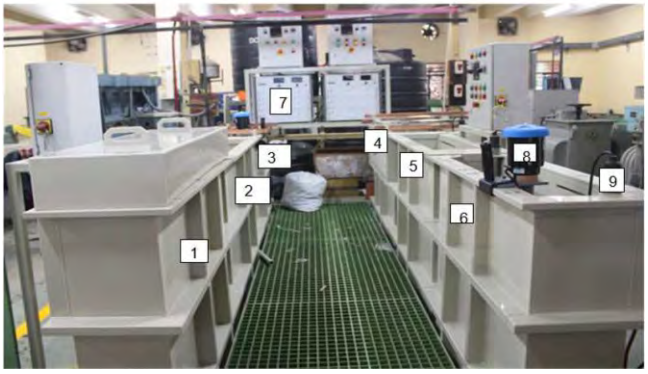
e) Trivalent Chrome Passivation: The Zn-Ni coated NCM steel disc and samples were thoroughly rinsed with distilled water followed by activation was done by immersion in 0.1v/v% HCl. The activated samples were immersed in Trivalent chrome passivation bath, process details are given in Table 6. EcoTriHC2 is a Chromium (III) containing thick layer passivation for zinc alloy which is completely free of Chromium (VI). The passivated disc is shown in Fig. 3.

Table 6: Trivalent Chrome passivation bath:

EcoTriCH2 (Cr III)	120 ml/L
Balance	Distilled water
pH	2.0
Temperature	Ambient condition
Time	30 secs

Fig.3: Zn-Ni plated and Trivalent chrome passivated disc.

The plating bath set up of 500 liter facility is shown in Fig. 4.



1.Mild Alkali Tank 2. Acid neutralizing tank 3.Nickel Strike Tank 4.Zn-Ni plating tank 5.Activation Tank 6.Passivation tank 7.Rectifiers – 2Nos 8. Pump 9 Heater

Fig.4: Zn-Ni plating 500 liter bath facility.

f) Hydrogen embrittlement relief Baking: The passivated samples were subjected to baking treatment at 190°C for 8 hrs to ensure the expel of hydrogen if any picked up during plating process. The baked specimens are shown in Fig. 5.

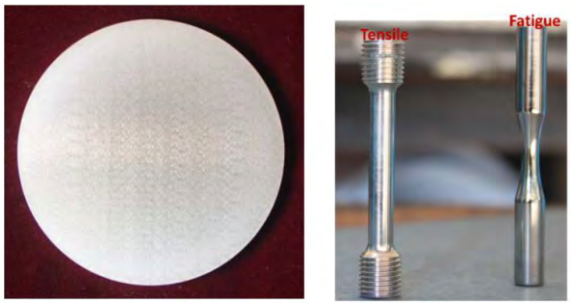


Fig.5: Post hydrogen embrittlement relief baking.

2.2 Qualification Testing:

After the baking process, all specimens were undergone qualification testing as per test matrix given in Table 4.

a) Visual Inspection: All the test coupons from each batch were visually examined for freedom from any surface irregularities like blisters, pits, porosity, cracks and any other defects.

b) Composition of Zn-Ni plating: One test coupon per batch of plated specimens was analyzed for chemical composition before passivation by EDAX method and the results were recorded.

c) Microstructure examination: Microstructure of one test coupon per batch was examined before and after post plating heat treatment by metallographic method at suitable magnification to report the micro-structural characteristics of the plating like microstructure, porosity, micro cracks, etc.

d) Plating thickness measurement: Three test coupons from each batch were subjected to plating thickness measurement before Passivation as per ISO 4518-1987 using optical microscope.

e) Adhesion Test: Adhesive property of the plating was tested on three test coupons from each batch using Elcometer 107 X- Hatch tester as per ASTM D3359. Also, bend test as per ASTM B571 was performed.

f) Hardness: Hardness of three test coupons after post plating heat treatment from each batch were tested as per ASTM E384. Hardness was also checked before post plating heat treatment for record purpose

g) Lubricity and Wear resistance by weight loss method: Two test coupons per batch were examined for lubricity using reciprocating wear test according to ASTM G133. The results were recorded for coefficient of friction and weight loss. The tests were performed using 6 mm alumina ball as counter material, load – 1N, stroke length – 10mm, frequency – 2Hz and duration – 20 min.

h) Corrosion resistance by Salt Spray(fog) test: One test coupon from each batch was subjected to salt spray (fog) test as per ASTM B117, to withstand minimum of 96 hours without indication of white corrosion product and minimum of 500 hours without indication of red corrosion as per AMS 2417J.

i) Tensile Test: Three test coupons per batch were tested for tensile strength. Ultimate tensile strength, 0.2% yield strength and % elongation was recorded.

j) Fatigue Test: Fatigue testing was carried out in rotating bending cantilever machine at Central Laboratory, HAL (F&F) at room temperature on three test coupons per batch. For comparison purpose fatigue test was also carried out on a test coupon without any coating.

k) Hydrogen de-embrittlement test: Hydrogen de-embrittlement test was carried out in accordance with ASTM F 519 (Type 1a.1) stressed in tension under constant load on
one test coupon from each batch.

l) Surface Roughness Measurement: Surface roughness measurement was carried out in accordance with the shop floor practice on one coupon from each batch by surface profile-meter and the results were recorded.

The Passivated Zn-Ni coated NCM steel was stripped by immersion in 10% HCl under ambient conditions for10 minutes. The samples were immediately removed and thoroughly washed with tap water and DM water. The bath analysis procedure with bath replenishment schedule was also prepared.

III. RESULT AND DISCUSSION

The primary objective is to replace existing Cadmium plating used in Aircraft industries. For comparison, few trials were carried out by using cadmium plating and the testing was done as per test matrix given in Table 4. The lubricity, corrosion resistance, hydrogen embrittlement tests found comparable with Cadmium plating. Fatigue and tensile tests are also comparable with the Cadmium plating. Three batches qualification testing of Zn-Ni plating were performed and results are discussed herewith.

The Zn-Ni plated specimens were found free from surface irregularities such as blisters, pits porosities, cracks when visually inspected. Slight discoloration observed, after the baking process which is acceptable as per AMS 2417J specification. The composition of the plating was checked as per EDAX method and found meeting the AMS 2417 requirement of 10-16 Wt% Nickel, the observed Ni was 12% while balance 88% is Zinc. The details are shown in Fig. 6.

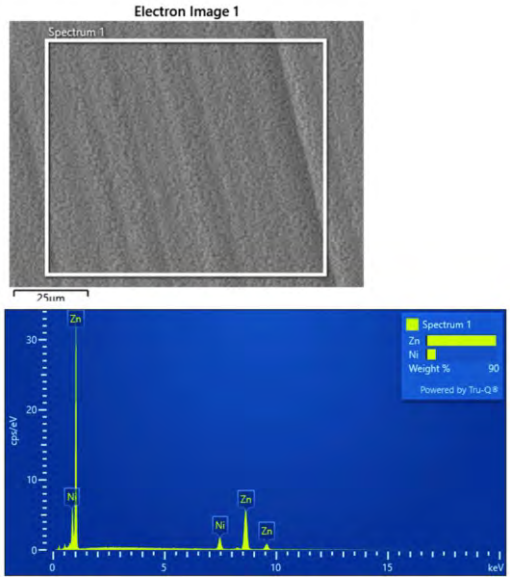


Fig.6: Chemical composition by EDX method.

The microstructure studies were performed by using Carl Zeiss Supra Field Emission Scanning Electron Microscope at CSIR-NAL. The microstructure of the surface of passivated Zn-Ni plated test specimen after baking was recorded. It is in compliance with the test matrix of Type Test Schedule. The SEM micrograph is shown in Fig. 7a & 7b.

Fig. 7a: SEM micrograph of plated surface

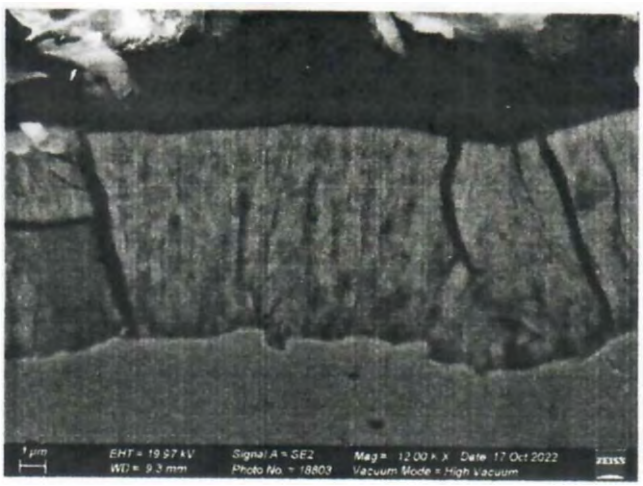


Fig. 7b: SEM micrograph of across the cross-section

Plating thickness was measured as per ISO 4518 – 1987 specification by using Leica DM IRM Optical Microscope. Measured thickness is in the range of 10-15 µm and this is in compliance with the test matrix of the type test schedule, as shown in Fig. 8.

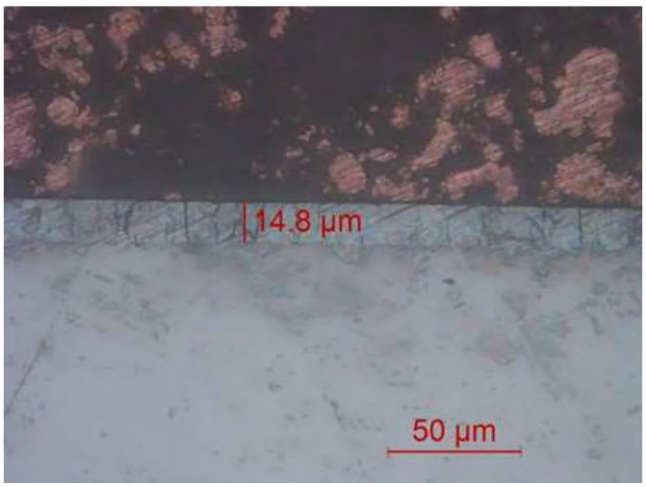


Fig. 8: Optical micrograph of Cross-Section of Zn-Ni plated specimen at 500X.

Baked passivated samples were subjected to cross-hatch adhesion test as per ASTM D3359 by using Elcometer Cross Hatch Cutter. No flaking or peeling off of Zn-Ni coating was observed [Fig. 9a]. One specimen was also tested by bend test, where no crack & peel off observed [Fig.9b]

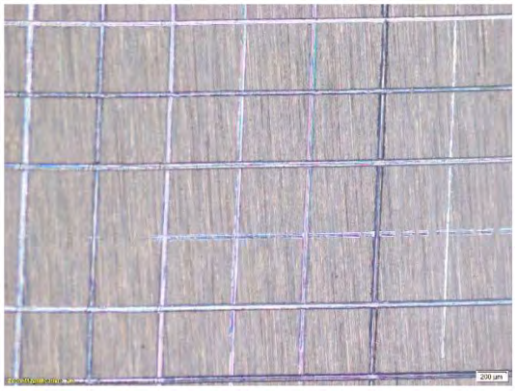


Fig. 9a: Cross-hatch image of Zn-Ni plated NCM Steel

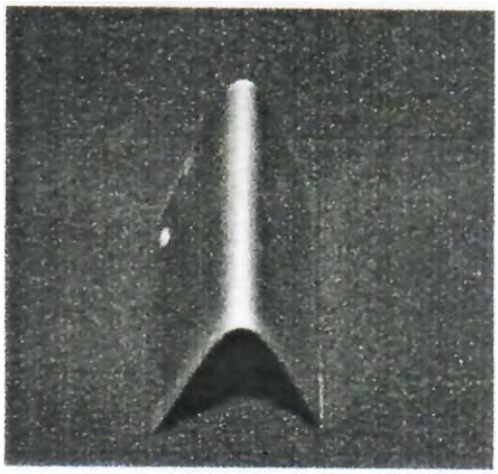


Fig. 9b: Zn-Ni plated Bend specimen

Microhardness test was performed as per ASTM E384 and found meeting the type test schedule requirement. The obtained average reading was 400 ± 35 HV. Lubricity and wear test were performed by using DUCOM Linear reciprocating wear tester as per ASTM G133 and the results are comparable with Cadmium plating. Corrosion performance was tested by using salt spray (fog) test as per ASTM B117 and AMS 2417J and observed passing the test 96 hrs for white rust and 500 hrs for red rust as per type test schedule requirements. The details are shown in Fig. 9.

Fig.10: Salt Spray (Fog) tested plated samples

Tensile and fatigue tests were carried out and found meeting the requirements of type test schedules. The hydrogen deembrittlement test was performed by using ASEC-453 Static load test tool and found meeting the requirements of min. 200 hrs static loading without failure as per ASTM F519

IV. CONCLUSION

1. The eco-friendly Zn-Ni plating process alternate to existing Cadmium plating has been developed successfully. Bath optimization, scaled up to 500 liters facility was established successfully at CSIR-NAL.
2. Type testing was carried on three batches in scaled up bath and found meeting the test schedule requirements.
3. The test results are comparable with Cadmium plating including adhesion, lubricity, wear, tensile, fatigue, corrosion resistance by salt spray (fog) test and hydrogen embrittlement.
4. The process can be used on Ni-Co-Mo steel, PH stainless steel and Cr-Mo steel for aircraft applications.
5. Airworthiness clearance for Zn-Ni plating process was obtained by airworthiness agency.

6. Finally, the Zn-Ni plating is recommended as an alternate to Cadmium plating for aircraft applications.

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High-Pressure Water Separation System Coupled with Aircraft Fuel in Environmental Control System for a Typical Aircraft Application

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Abstract / Executive Summary - A fighter aircraft environmental control system (ECS) maintains a safe and pleasant cabin for passengers and avionics. In this study, the bleed air ECS of a fighter aircraft was integrated with an existing fuel to obtain thermodynamic characteristics in terms of the overall energy optimization and coefficient of performance (COP). A closed-loop algorithm was designed using MATLAB coding to calculate the performance of all components. The results show that the integration of air-fuel heat exchangers increases the cooling capacity of the bleed air ECS under the same operating conditions as the existing ECS. This system increased the efficiency of the bleed air system and reduced the fuel energy consumption by 1.64%. An increase of 11.36% in the overall COP of the system was observed. The MATLAB model can acquire the thermal performance of the ECS at the system and component levels, which can help aircraft manufacturers analyze the performance and provide requirements to component suppliers.

Keywords - bleed air system, environmental control system, fighter aircraft, fuel supply

I. INTRODUCTION

The crew and electronic equipment inside the cabin require a reliable environmental control system (ECS). The goal is to maintain a comfortable cabin environment regardless of external conditions [1]. Aircraft have evolved to the point where they need to transport increasingly sophisticated electronic warfare, radar, and other avionic components [2,3]. To ensure the well-being of the aircraft payload (goods, living cargo, and human cargo), an ECS is in place to regulate the internal environment of the cabin (temperature, pressure, and composition) to within predetermined limits [4,5]. It has been calculated that the ECS accounts for 75% of the total power consumed by the secondary power systems, which is between 3% and 5% of the power generated by the engine [6]. However, several ECS configurations exist, each of which has its own system size, cost, and dependability. Therefore, it is important to strike a balance between cabin comfort, bleed air requirements, and system cost [7,8]. Regular ECS setups use the high-compressor stage of the engine to draw out hot, compressed, and bleed air. The air-conditioning pack has a pressure reducer, precooler, primary heat exchanger (P-HX), cold air unit (turbine and compressor), secondary heat exchanger (S-HX), reheater (R-HX), condenser (C-HX), water separator (WS), and other valves [9,10]. The traditional ECS uses a Reverse Brayton cycle for air conditioning. The ECS traditionally uses engine-bleed air to regulate cabin temperature and pressure for passenger comfort and avionic temperature [11-13]. This reduces the aircraft's efficiency and fuel consumption because extracting compressed bleed air from the engine reduces thrust. An ECS can also be classified into high-pressure and low-pressure systems, based on the

location of the water separator (upstream or downstream of the cooling turbine) [14,15]. The air cycle system (ACS) applications in different aircraft are listed in Table I.

The aim of this study is to propose a novel three-wheel ECS for a traditional (bleed air) fighter aircraft using aircraft fuel while maintaining outlet pressure, and the temperature remains the same with the help of MATLAB programming. The performance of the new system was analyzed by comparing it with a traditional system in terms of the fuel energy consumption rate (FECR) and coefficient of performance (COP). The new system was verified using a reference study of an ECS with a water tank [16].

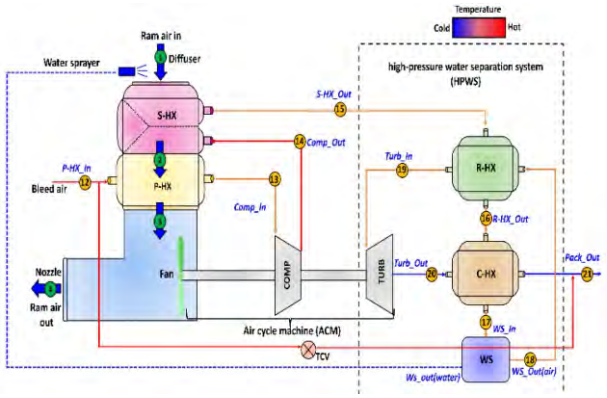
TABLE I APPLICATION OF DIFFERENT ACS

System type		Application aircraft
Two-wheel simple system		XC-35, AN-24, IL-18, IL-62, M-19, M-21
Two-wheel bootstrap system	Low-pressure water separation	B707-300, B727, B737-300, B737-500, MD-80, MD-90, DC-9
	High-pressure water separation	F-18, T46A, B737-400, ATR-72
Three-wheel system	Low-pressure water separation	MD-95, A300, A310, B747-400, DC-10, L-1011, B737-600, B737-700
	High-pressure water separation	A320, A330, A340, BAE-146, B737-800, B737-900, B747-800, B757, B767, B787(E-ECS)
Four-wheel system		B777, A380

II. SYSTEM DESCRIPTION

A. Traditional Three-wheel ECS

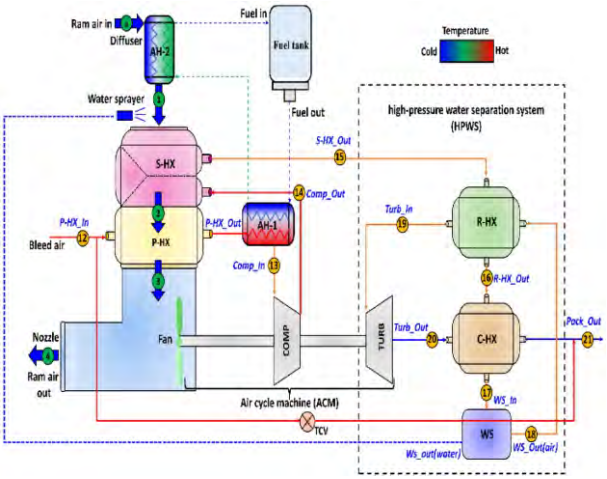
Fig. 1 illustrates the ECS primary and secondary heat exchangers, cold air unit (CAU), condenser, reheater, and water separator. The ECS uses ram and bleed air for air conditioning. Fig. 1 shows a diffuser that introduces ram air into the ECS. The secondary and primary heat exchangers sequentially cooled the extracted bleed air from the main engine. After the heat transfer, the fan accelerated and expanded in the nozzle to create thrust. To prevent ice forming at the ACM turbine outlet, the air-conditioning pack included a water extraction loop. This is achieved by directing the airflow in the pack in such a way as to separate the water molecules as part of the air conditioning process. P-HX is the first step in cooling the heated air in the ACM compressor section. The air was further cooled in the condenser below the dew point. Small water droplets were formed in the condenser and collected for removal. The vortex created by the water extractor pulls water molecules from the high-pressure ACM. The ACM turbine inlet receives dried air heated again in the R-HX. Injectors inject the extracted water into the ram air inlet to improve the cooling efficiency.



P-HX -primary heat exchanger; COMP- ACM compressor; S-HX- secondary heat exchanger; R-HX- reheater; C-HX- condenser; WS- water separator; TURB- turbine

Fig. 1. Schematic diagram of traditional three-wheel bleed air HPWS ECS

B. Novel three-wheel ECS with aircraft fuel



P-HX -primary heat exchanger; COMP- ACM compressor; S-HX- secondary heat exchanger; AH-1- bleed air-fuel heat exchanger-1; AH-2- ram air-fuel heat exchanger-2; R-HX- reheater; C-HX- condenser; WS- water separator; TURB- turbine

Fig. 2. Novel three-wheel bleed air HPWS ECS with fuel tank

This study proposes a new three-wheel bootstrap high-pressure water separation air cycle system (HPWS) coupled with a cold fuel supply for a fighter aircraft ECS. Unlike a traditional three-wheel HPWS, as shown in Fig 1., the new system integrates air-fuel heat exchangers after the P-HX and before the S-HX. Bleed air-fuel heat exchanger-1 (AH-1) heated the cold fuel in hot side and cold-side ram air-fuel heat exchanger-2 (AH-2) receives low-temperature, low-pressure ram air outside the cabin after being preheated by hot fuel. High-temperature bleed air heats the cold fuel from the fuel tank, which enters bleed AH-1 at a constant flow rate, and the heated hot fuel enters ram AH-2. Low-pressure, low-temperature ram air was preheated using a hot fuel. After releasing a large amount of heat, the fuel cools to the same temperature as the fuel tank and flows back into it, thereby forming a self-circulation mode.

TABLE II ECS INITIAL CALCULATION PARAMETERS

Cruising conditions			
Flight height (km)	11	Mach number	0.82
Heat load (cabin and avionics) (kW)	20		
Ground conditions			
Flight height (km)	0	Mach number	0.2
Heat load (cabin and avionics) (kW)	13.5		
Efficiencies			
ECS turbine	0.809	ECS compressor	0.72
P-HX 0.7	0.7	S-HX	0.75
Reheater	0.5	Condenser	0.4
Ram air diffuser	0.95	Ram air nozzle	0.9
AH-1 (Water)	0.72	AH-2 (Water)	0.39
AH-1 (Fuel)	0.72	AH-2 (Fuel)	0.5
Ram/Bleed air			
Ambient temperature (K)	216.8	Bleed air temperature (K)	485
Ambient pressure (kPa)	17.89	Bleed air flow Rate (kg/s)	0.31
Ram air temperature (K)	248.13	Bleed air pressure (kPa)	210
Ram air pressure (kPa)	28.06	Compressor pressure ratio	1.48
Total specific humidity (g/kg of dry air)	12	Turbine pressure ratio	3.2
Ram air flow rate (kg/s)	0.56	Fan pressure ratio	1.2
Water			
AH-1 mass flow rate (kg/s)	0.16	AH-2 mass flow rate (kg/s)	0.16
Water inlet temperature (K)	293	Water outlet temperature (K)	316.5
Fuel			
AH-1 mass flow rate (kg/s)	0.34	AH-2 mass flow rate (kg/s)	0.16
Fuel inlet temperature (K)	293	Fuel outlet temperature (K)	337.34

III. MATHEMATICAL MODELLING

An ECS is a complex coupled system comprising many different components. Predicting the component performance is impossible because of changing flight conditions. MATLAB was used to create the ECS numerical calculation model. Table II lists the air composition and flight envelope parameters as boundary conditions for the traditional and novel ECS. By changing these parameters, the control strategies can be simulated for the ECS under different flight conditions.

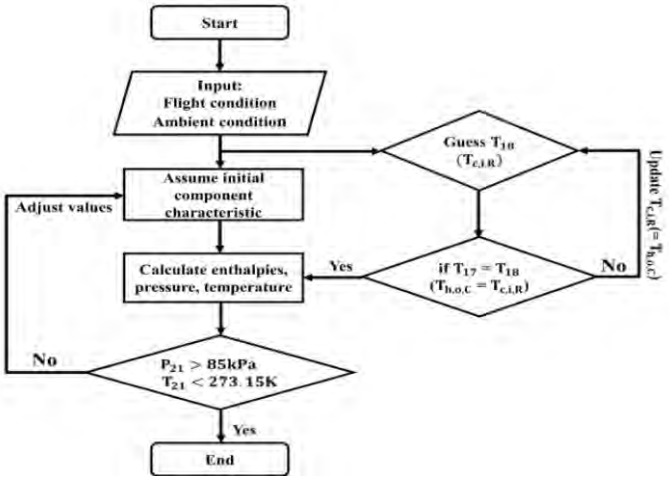


Fig. 3. Algorithm flow chart for MATLAB coding

A. Ram air calculation

The inlet temperature and pressure of the ram air were calculated as in (1) and (2), respectively, using the aircraft velocity and Mach number.

$$T_{ram} = T_{amb}\left(1 + \left(\frac{\gamma-1}{2}\right)Ma^2\right) \quad (1)$$

$$P_{ram} = P_{amb}\left(1 + \eta_d\left(\frac{\gamma-1}{2}\right)Ma^2\right)^{\left(\frac{\gamma}{\gamma-1}\right)} \quad (2)$$

B. Heat exchanger calculation

The thermal efficiency of the heat exchanger can be used to determine the outlet temperature. The energy balance equation is as follows:

$$T_{h,o} = T_{h,i} - \eta_{HX}(T_{h,i} - T_{c,i}) \quad (3)$$

$$T_{c,o} = \frac{m_h(T_{h,i} - T_{h,o})}{m_c} + T_{c,i} \quad (4)$$

Bernoulli's equation and the fluid continuity principle determine the outlet pressure of the heat exchanger:

$$P_{h,i} - P_{h,o} = \frac{1}{2\rho_h}\left(\frac{\dot{m}}{k_h}\right)^2 \quad (5)$$

$$P_{c,i} - P_{c,o} = \frac{1}{2\rho_c}\left(\frac{\dot{m}}{k_c}\right)^2 \quad (6)$$

C. Air-fuel heat exchanger

An air-fuel heat exchanger provides hot fuel for aircraft in the novel system. The thermodynamic equation of the air-fuel heat exchanger is given by (7).

$$m_{bleed}C_{pa}(T_{h,i} - T_{h,o}) = m_f C_{pf}(T_{w,o} - T_{w,i}) \quad (7)$$

D. Air cycle machine

The turbine, compressor, and fan share a shaft. The turbine powers the compressor and fan. The compressor, turbine, and fan powers are given by (8) and (9).

Compressor / Fan:

$$T_o = T_i + \left[1 + \frac{1}{\eta_c}\left(\left(\frac{P_o}{P_i}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)\right] \quad (8)$$

Turbine:

$$T_o = T_i + \left[1 - \eta_t\left(1 - \left(\frac{P_o}{P_i}\right)^{\frac{\gamma-1}{\gamma}}\right)\right] \quad (9)$$

The power balance of ACM is

$$W_c = W_t + W_f \quad (10)$$

E. Reheater-condenser calculations

The R-HX and C-HX outlet temperatures were calculated using enthalpy balance equations:

$$m_h(1+\omega_h)(h_{h,i} - h_{h,o}) = m_c(1+\omega_c)(h_{c,o} - h_{c,i}) \quad (11)$$

The enthalpy of the fluid streams was calculated as follows:

$$h = \frac{c_{p,a}t + \omega(r + c_{p,v}t) + (\omega_T - \omega)c_{p,w}t}{1+\omega_T} \quad (12)$$

The specific humidity in vapor form was calculated as follows:

$$\omega = 0.622\left(\frac{P_v}{P_t - P_v}\right) \quad (13)$$

P_v is calculated using the Antoine equation as follows:

$$log_{10}P_v = 8.2024325 - \frac{1736.2356}{t+234.5} \quad (14)$$

F. New ram air/S-HX cold inlet temperature calculation

The final (new) ram air temperature after the water spray was calculated as follows: As shown in Fig. 3, point 1 (ram air inlet), point 2 (extracted water spray from WS), and point 3 (new ram air after mixing). Point 3 is the cold air inlet of the S-HX.

$$T_{new\ ram} = T_{ram} - \frac{(\omega_{new\ ram} - \omega_{ram})(h_{v,ram} - h_{w,ws})}{C_p a_{ram} + x_{new\ ram} C_p w_{v,ws}} \quad (15)$$

$$\omega_{new\ ram} = \omega_{ram} + \frac{m_w}{m_{ram}} \quad (16)$$

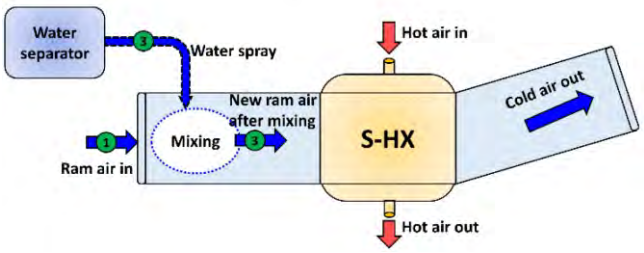


Fig. 4. Water spray mixing with ram air

G. Energy consumption calculations

The ECS is powered by intermediate-compressor high-pressure bleed air, which drives the turbine. All energy in the ECS originates from fuel combustion, including mechanical and internal energy.

Power consumption of the diffuser ($E_{d,bleed}$)

$$E_{d,bleed} = m_{bleed}\left(\sqrt{\gamma RT_{amb}}\,.Ma\right)^2/\eta_p \quad (17)$$

Fuel energy consumption of the compressor ($E_{c,bleed}$)

$$E_{c,bleed} = m_{bleed}\,h_{bleed}/\eta_{th} \quad (18)$$

$$h_{bleed} = c_p(T_{bleed} - T_{ref,amb}) \quad (19)$$

$$T_{ref,amb} = T_{amb}\left[1 + \left(\frac{\gamma-1}{2}\right)Ma^2\right] \quad (20)$$

Total energy consumption of the bleed air (E_{bleed})

$$E_{bleed} = E_{d,bleed} + E_{c,bleed} \quad (21)$$

Ram air energy consumption is the difference between diffuser power consumption and nozzle propulsive power.

$$E_{ram} = E_{d,ram} - E_{n,ram} \quad (22)$$

$$E_{d,ram} = m_{ram}\left(\sqrt{\gamma RT_{amb}}\,.Ma\right)^2/\eta_p \quad (23)$$

$$E_{n,ram} = m_{ram}v_{out}\sqrt{\gamma RT_{amb}}\,.Ma/\eta_p \quad (24)$$

Extra drag can be used to calculate the energy consumption owing to the extra weight of the heat exchanger ($E_{HX,m}$).

$$E_{HX,m} = D_E\sqrt{\gamma RT_{amb}}\,.Ma/\eta_p \quad (25)$$

The extra drag can be determined by the heat transfer area (A_{HX}), the ratio of A_{HX} to the weight $m_{HX}(\beta)$, and the lift-drag ratio (K).

$$D_E = m_{HX}g/K = (A_{HX}\beta)g/K \quad (26)$$

For a tube-shell heat exchanger, the recommended range of β is 2-4 kg/m². Therefore, it was set as 3 kg/m². K is set to 18.2.

Fuel Energy Consumption Rate (FECR):

$$FECR_{bleed} = E_{bleed} + E_{ram} + E_{HX,m} \quad (27)$$

H. Performance comparison

To investigate the performance of the ECS, an analysis was performed based on three parameters: the power demand, coefficient of performance (COP), and FECR.

Therefore, the cooling capacity of the cabin (Q_{cool})

$$Q_{cool} = m_{bleed}c_p(T_e - T_{O,cabin}) \quad (28)$$

Input power (W_i)

$$W_i = m_{bleed}c_p(T_{bleed} - T_{ram}) \quad (29)$$

The COP of existing and proposed energy-efficient ECS is

$$COP = \frac{Q_{cool}}{W_i} \quad (30)$$

IV. RESULT AND DISCUSSION

A. Component-level analysis

The numerical method described in Section (III) were used to model the traditional and new ECS for fighter aircraft at ground and cruising. The initial parameters of the ECS were obtained from Table (II). Figs. 5 and 6 show the component-level temperature and pressure profiles at the outlet of each component of the fighter aircraft. In a traditional fighter aircraft, the ECS lacks air-fuel heat exchangers because the compressor inlet temperature and pressure are higher than those of the novel system. The benefit of using an air-fuel heat exchanger is that it decreases the engine bleed air temperature after the P-HX before entering the compressor, which requires less compressor work to run the system.

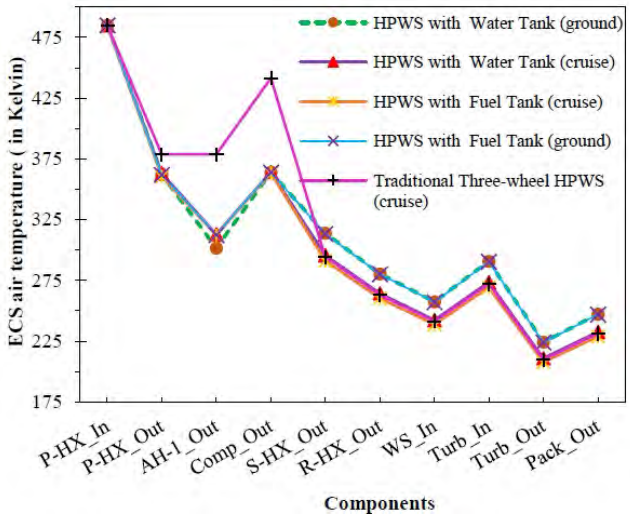


Fig. 5. Component level temperature profile

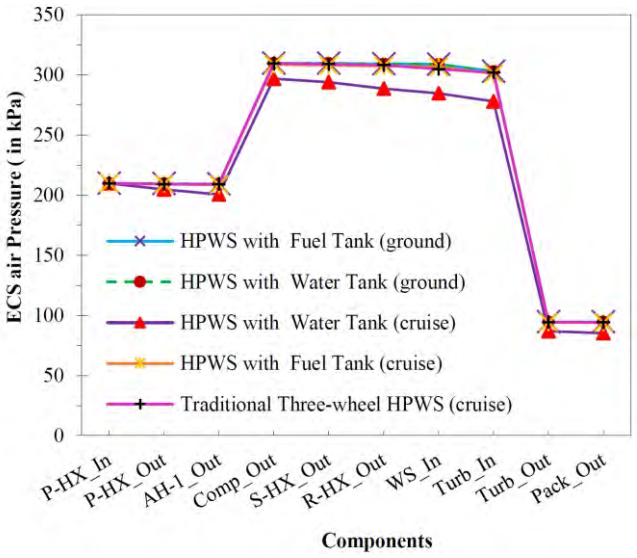


Fig. 6. Component level pressure profile

The MATLAB ECS was modelled such that the pack inlet temperature and pressure satisfied the cabin requirement and the temperature at the inlet of the turbine exceeded 0°C to avoid ice formation. The temperature can be maintained using a temperature control valve (TCV) by mixing trim air.

B. Performance analysis

The performances of the traditional and novel systems were rated on the basis of the COP and energy consumption. The COP of the traditional three-wheel ECS was 0.39, as shown in Fig. 7. As in the novel ECS, the COP was 0.44. It was observed that when the existing fuel tank was equipped in the ECS to provide cold fluid in the air-fuel heat exchanger, an increase in the COP was observed because the engine bleed air temperature and pressure reduced twice before entering the compressor. However, the cold fuel outlet temperature in air-fuel heat exchanger-1 reaches 337 K, which is again sent back to the fuel tank after cooling in air heat exchanger-2 through ram air. From the validation point of view, the same study was conducted using a water tank in place of a fuel tank, and the value of COP was obtained as 0.43. This requires an extra tank of water for the ECS in a fighter aircraft. However, in the case of passenger aircraft, an additional water supply is not required. Similarly, for fighter aircraft, existing fuel from the fuel tank is utilized for cooling in air heat exchangers, which do not require an extra fuel supply.

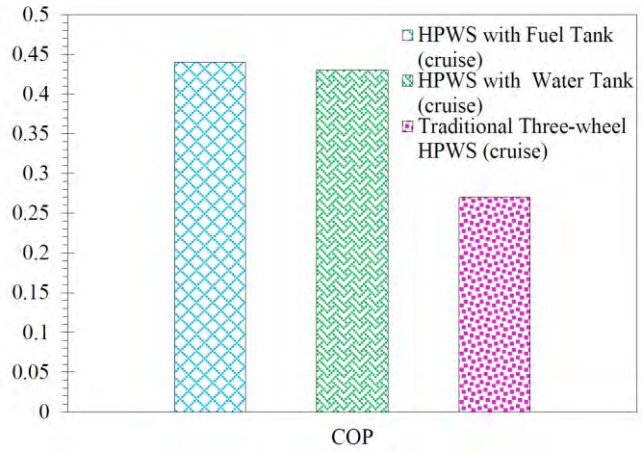


Fig. 7. COP comparison

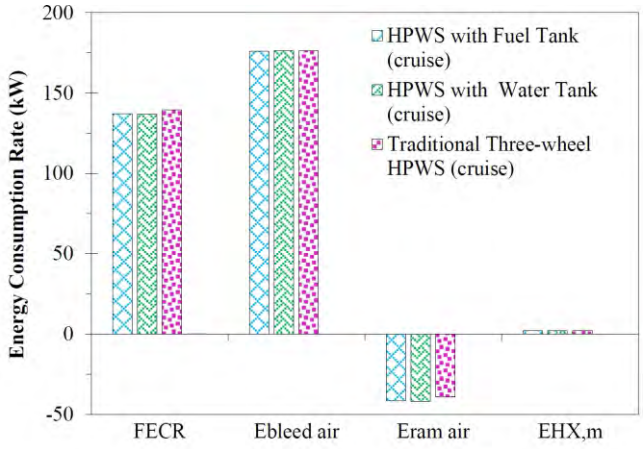


Fig. 8. Energy comparison

The energy comparison of the traditional and novel ECS was calculated on the basis of bleed air and ram air extraction via the diffuser and compressor. The total fuel energy consumption rate was calculated as the sum of the total bleed air, ram air, and extra weight of the heat exchangers. The ram air energy consumption is negative because ram air provides propulsive power with the input energy from the fan and HX. The FECR for novel and traditional ECS are 137.1 kW, 139.4 kW respectively shown in Fig. 8 in which extra energy consumption due to a heat exchanger was calculated as 2.32 kW.

CONCLUSION

With the correct design, the ECS could use the three-wheel bootstrap HPWS with water spraying to improve the performance of the existing bleed

air ECS for fighter aircraft. The integration of AH-1 and AH-2 into the ECS improves the performance of the system. The benefit of using AH-1 is to decrease the bleed air temperature one more time before it enters the compressor. This results in a lower outlet temperature of the compressor. The cold fuel from the fuel tank entered AH-1 at 293 K and exited heat with the bleed air at 337 K, which is less than the autoignition temperature of the fuel. The heated fuel is sent to AH-2, where it exchanges heat with cold ram air, and its temperature drops to 293 K and returns to the fuel tank. This method is known as the self-circulating mode. It can be stated that even with high bleed temperatures, a sufficient fuel flow rate is to be maintained; otherwise, stop the fuel to heat exchangers if the fuel temperature reaches the flash point. During the short-duration landing phase, a higher ECS temperature is acceptable. The MATLAB model can acquire the thermal performance of the ECS at the system and component levels, which can help aircraft manufacturers analyze the performance and provide requirements to component suppliers. The main aim of this study was to enhance the performance of a traditional bleed-air ECS for fighter aircraft by using in-house fuel tanks. The COP of the system was enhanced by 11.36% and the energy consumption was reduced by 1.64%. The weight penalty owing to the additional components is approximately 6-8 kg. This weight was included in the fuel penalty calculations. During the landing phase, the aircraft must land with minimum fuel, and optimization of the fuel flow rate to the heat exchangers is to be carried out during the detailed design of the system components. The new system does not require an extra fuel supply to run the ECS. For validation purposes, the same study was conducted using a water tank in a passenger aircraft.

However, this case is possible for passenger aircraft in future studies.

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NOMENCLATURE

Variables

c_p	specific heat at constant pressure, kJ/(kg.K)
$c_{p,a}$	specific heat of dry air, kJ/(kg.K)
$c_{p,v}$	specific heat of vapour, kJ/(kg.K)
$c_{p,f}$	specific heat of fuel, kJ/(kg.K)
$c_{p,w}$	specific heat of water, kJ/(kg.K)
C_{p,w_v}	specific heat of water vapor at constant pressure (kJ/kg.K)
D_E	drag, N
g	acceleration due to gravity, m/s^2
h	enthalpy, kJ/kg
k	geometric factor
K	lift-to-drag ratio
m	mass flow rate, kg/s
Ma	Mach number
P	pressure, bar
P_t	total pressure, bar
P_v	partial pressure of water vapour in the fluid, bar
R	air constant, J.mol^{-1}.k^{-1}
r	latent heat of vaporization, kJ/kg
t	dry bulb temperature in °C
T	temperature, K

Greek symbols

γ	ratio of specific heats
η	effectiveness or efficiency
η_c	compressor efficiency
η_d	diffuser efficiency
η_n	nozzle efficiency
η_p	propulsive efficiency
η_{th}	thermal efficiency
η_t	turbine efficiency
ω	specific humidity in vapour form (g/kg of dry air)
ω_T	total specific humidity (g/kg of dry air)
ρ	density, kg/m^3
v	velocity, m/s

Subscript

amb	ambient	h, i	hot inlet
bleed	bleed air	h, o	hot outlet
c	cold	HX	heat exchanger
cabin	cabin air	i	inlet
c, i	cold inlet	o	outlet
c, o	cold outlet	*ram*	ram air
e	exhaust	ref	reference
h	hot		

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Optimization of Composite Material For Cargo Bike Frame

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Abstract - Nations world wide are forming policies to reduce emissions due to human industrilization and urbanization. Transport industry has registered a growing trend emissions due to increased logistics of material. E-Cargo Bikes are suitable mode of transport with reduced emissions for for private and commercial mobility. This study is based on design of a suitable E-Cargo bike with a a comprehensive selection appropriate material for strength and stiffness criterion. Composites with its enhanced mechanical and thermal properties, resistance to corrosion and its varied structural forms has made a paradigm shift in manufacture of commercial automotive and aerospace in transportation. But composites being orthotropic requires an extensive analysis regime to evaluate the performance characteristics in multi-direction of orientation. Hence this study proposes to undergo parametric analysis of Fiber Reinforced Plastic and Metal Matrix composites. The optimized composite configuration will be used for the frame of the cargo bike and evaluated for its static and dynamic characteristic in comparison to its steel and Aluminum counterparts and check to achieve the target performance. The choice of a material lies in its performance characteristics and its feasibility of production. To achieve world sustainability vision an embodied carbon of the parts and process shall be undertaken to achieve a complete holistic approach of design.

Keywords - Composites, Manufacturing Feasibility, Structural Analysis, Simulation Driven Design

I. INTRODUCTION

The advancement in material and design technology has enabled a systematic simulation engineered design decisions to generate optimized end product design meeting target performance. Light weight design directly goes to reduction in fuel and fuel energy accompanied emissions. Transport industry is primary faction involved in reduced air quality index especially withing urban cities due to uncontrollable traffic volume and need for design studies to tackle minimized emission of automotive parts is of fundamental requirement. A study by has identified transport sector to be contributor of 14% of CO2 due to direct energy related emissions. Withing transport sector road transport is said to have contributions of 90% of the emissions.

Cargo bikes are powered by human work with addition of electrical assistance having the capability to move A to B with minimal harmful emissions. In Ecargo bikes the battery has a range of 50 – 80 km with carrying capacity of 50 – 250 kg call E-Cargo bikes [1], [2]. This paper studies on the selection of a suitable material for the E-cargo frame developed by M/s Altair India Private Limited.

Composites possess the maximized mechanical and thermal properties greater than that achieved by the individual constituents' materials. They contribute to light weight, higher strength, chemical resistance and enhanced mechanical properties. Composites are primarily classified into Polymer Matrix, Metal matrix and Ceramics matrix systems. The design optimization studies are carried to understand and evaluate the behaviour of the different composites available for the automotive industry and through a formative decision assessment among Performance, Cost, Manufacturing, Availability, Scalability and Recyclability of the selected material enable to identify a suitable selection to enable Light-

weighting to achieve reduced carbon Footprint.

Polymer matrix are of thermoset and thermoplastic where thermosets are well established system that provide high specific modulus and specific strength. Thermoplastics are relatively subordinate but provide the required performance with greater extent of recyclability. Fibers are primarily incorporated in polymer composites as reinforcing agent that are Carbon, Glass, Kevlar and in addition with natural fibres as continuous, short and particulate. The primary advantage is the formation of laminate-based shapes that can be optimized to have specific stiffness through ply orientation in the strength required directiom and of necessary thickness with ply-drops

Metal Matrix composites comprises of metal of lighter weight and reinforcing fibres of long, short or whisker and particulate system. Among the fibre variation extensive research has been conducted on particulate fibres which are considered to be easily fabricated and processed. It is observed that short whiskers pose health issues due to challenges in handling and production. It was observed by [4] that reaction of Al2024 metal matrix with TiC fibres of 52% & 55% fabricated using pressureless infiltration process recorded the major phases observed to be CuAl2 and TiC with other metallic phases being CuAl2, TiAl3, TiAlC and AlTi3 Varied densification were observed at temperature 1350 oC and 1450 oC with higher densification of TiC at 1450 oC showed an increase in hardness. TiC particles when forming an interconnected network structure leads to higher strength. The studies by [3] noted the refining of microstructure of Aluminium composites consisting of Al 6061 with Al2O3 matrix by rolling and T-6 temperament. It was observed that T6 treatment increased the hardness of the Al composites. In the studies the variation of Al2O3 reinforcement of varying percentages of 10%, 15% and 20% were evaluated and it was concluded that higher wear resistance was identified at room temperature and elevated temperature of 150 oC with increase of the fibre percentage.

Apart from design verification a deciding factor playing a crucial role in selection of automotive material is the prospect of scalability of production and machining. Numerous fabrication techniques and joining techniques are adopted by researchers and industries which are reviewed below.

Stir Casting route is considered to be a economic fabrication route for MMC's. This method can be employed for fabrication of AMMC's of complex profiled sections without damaging reinforcement particles. Pressureless infiltration technique of liquid metal infiltration process in which the reinforcement preform is prepared and the molten metal matrix infiltrated at necessary pressure [4]. In their study fabrication process adopted was pressureless infiltration where TiC preforms were sintered under argon atmosphere for 90 min at 1350°C and 1450°C and formed by lattice diffusion of matrix transport. Reinforcement levels of above 50% to 80% is required. Another variation of the technique is spray deposition and in-situ processing which is considered to be relatively inexpensive to P/M processes.

Multiple production routes have been established for fibre reinforced polymer systems where the fibre laminates are pre-placed and adhesive is infused through injection which are observed in Split Mould-Vaccum Bagging, Reaction Injection Moulding while in the case of Resin Transfer Moulding the fabrication assisted through compression force. Laser Assisted Tape Placements are used for the precise layups and automation of process routes. Tubular structures are fabricated through Bladder Assisted Resin Transfer Moulding and Filament Winding Processes.

Another processing aspect for the viability for material selection is Joining. Aluminium based Alloys and Composites are a suitable material option for automotive for its low density providing higher strength for lower weight, presence of native oxide layer making resistant to deterioration in corrosive environment and lower thermal expansion [8], [9]. But during fusion welding the direct heat application of electric arc beyond the

melting point of the Aluminium is responsible for reduced mechanical properties. Hence a indirect electric arc (IEA) technique combined with Metal Inert Gas (MIG) welding is proposed where the IEA follows placing a piece feed metal aligned properly having similar characteristic of metal and filler material.

Hence from the study it can be observed that Composites can be used for automotive applications having significant research work for scaling options for manufacturing and joining of components. Fiber Reinforced Polymer Composites pose a greater opportunity to optimize thickness at concentrated at particular region specific.

II. METHODS

The analysis shall be studied on models developed for each case pertaining to parametric requirement of the Electric cargo Two-Wheeler. The design optimization for the alternate material that is Metal Matrix Composite material shall be realized in the following systematic approach as given below:

- Analysis of the Baseline Cargo Two-Wheeler model performance with standard material and section
- Identification of the Design Space in Two-Wheeler model for the Optimization
- Development of the Design Verification Plans
- Structural Analysis of the Optimized Frame
- Subsequent optimization for the Section and Material
- Comparison of results between different material and section for which results are charted
- Conclude the best result optimized from simulation models with respect to both weight and performance characteristics
- Evaluation for manufacturing feasibility

III. CARGO FRAME ANALYSIS

A. Geometry Description

The round off dimensions of the cargo model developed by Altair India is 2045 mm (X-aixs) X 683 mm (Y-axis) 710 mm(Z-axis). AS4010 Steel is the predominant material used for the primary sections of the cargo frame. To introduce weight reduction alternative materials are considered including Aluminium alloy Al 6061 and Metal Matrix Composite of Al 2024-TiC (55%) & Al 359 SiC (30%).

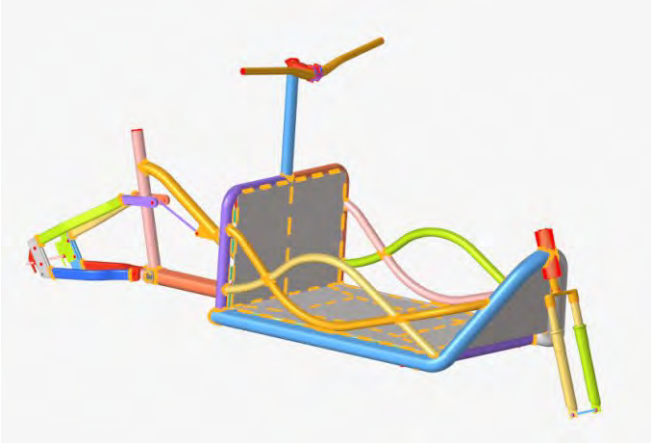

Fig. 1 Cargo Frame

B. FEA Model Description

The 2-D Cargo frame FE model has been developed by using Altair Hyper Mesh software. The average element size of 5mm, the variable thickness of the cargo frame as follows. Thickness of main frame tubular structure is 2mm, floor supporting structure is of 2.3mm and side supporting structure 3.2mm along with Rear frame

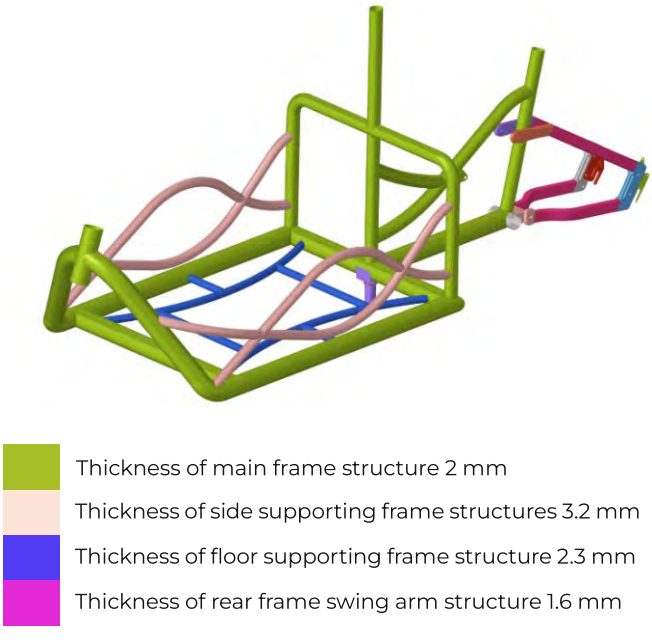

Fig. 2 Sectional thickness Variation

swing arm tube thickness is 1.6mm respectively. Connection of frame structure represented by seam weld -hex rb3 penta(mig) weld of 2.5mm width.

C. Design Verification Plans

The Altair Hyperworks Optistruct Solver is used to obtain the below Design Verification Plans (DVP) and Hyperview is used for the Post-processing of the results.

1) Modal Case - Modal Analysis
2) Steering Load - 100 N Couple Force on Handle Bar
3) Rider Force - 1000 N on seat
4) Bending - 1000 N on center of cargo
5) Torsion - 1000 N Upward & Downward along width of the frame
6) Battery Loads - 200 N on Battery Mount

IV. MATERIALS

The baseline materials used for the study are Steel of grade AS 4010. For comparison mechanical properties of Al6061 is also taken. The properties of the composite materials comprising of Metal Matrix composites and Fiber Reinforced Polymer Composites are given in Table 1 & Table 2 respectively. For the present analysis Metal Matrix Composite Material adopted from the literature studies are Al 2024-TiC (55%) & Al 359 – SiC (30%). The material naming is given as St for AS4010, Al for Al6061, AT55 for Al 2024 – TiC 55% and AS30 for A359 – SiC 30%. Also, Al6061-4%SiC is considered for the study under process. Another study of Carbon and Glass fiber epoxy is also to be optimized to tabulate assessment parameters.

Table 1. Mechanical Properties of Metal Matrix Composites

No.	Material	E (Gpa)	ν	P (g/cc)
1.	AS4010	210	0.29	7.85
2.	Al60601	69	0.3	2.7
3.	A359 – SiC 30 %	120	0.33	2.8
4.	Al2024– TiC 55%	203	0.33	2.97
5.	Al6061- SiC 4%	97.25	0.32	2.73

Where E is Elastic Modulus, Nu is Poisson's ratio, ρ is density

Table 2. Mechanical Properties of Fiber Reinforced Polymers

No.	Material	E1 (Gpa)	E2(Gpa)	ν	P (g/cc)
1.	Carbon/Epoxy	203	7.9	0.34	1.55
2.	Glass/Epoxy	37.6	6.5	0.35	1.74

Where E1 is Longitudinal Elastic Modulus,
E2 is Lateral Elastic Modulus,
Nu is Poisson's ratio, ρ is density

V. RESULT & DISCUSSIONS

The stress and displacement results obtained for the above Load Cases are tabulated in Table 3. From the modal analysis the observation for the comparison is taken till 100 Hz. For the present studies the Lateral, Bending and Torsional modes are taken from the post-processing which is given below Figures 3.,4 and 5. To formulate a better understanding of the material the Bending and the Torsional stiffnesses as calculated in Table 3.

The modal analysis observations has provided the stress concentration in the critical areas. A similarity of the results is observed between Steel and Aluminium Composite reinforced by TiC with 55% particulate fibers. From the stiffness curve it can be interpreted that though the material change has provided a significant contribution to 50% mass reduction a relative decrease in stiffness values can be identified

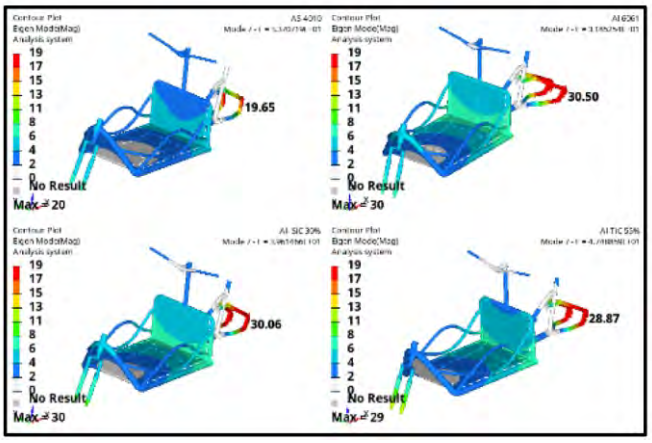

Fig. 3. Lateral Mode from Modal Analysis

Table 3. List of DVPs

Base Model		Conventional Material		AMMC	
Load Cases	Results	Steel-4010	Aluminium_6061	AlSic30%	AlTic55%
Modal Analysis	Torsional Frequency (Hz)	57.79	53.16	59.3	63.67
	Bending Frequency (Hz)	43.27	41.10	50.01	56.67
	Lateral Frequency (Hz)	33.707	31.85	39.61	47.48
Steering Load	Displacement(mm)	2.68	4.46	3.51	2.75
	Stress (Mpa)	67	42	55	66
Rider Load/Force	Displacement(mm)	4	8	6	4
	Stress (Mpa)	288	264	271	281
Bending Load	Displacement(mm)	2	4	3	2
	Stress (Mpa)	107	118(90)	98	105
Torsion Load	Displacement(mm)	84	192	124	86
	Stress (Mpa)	1308	1078	1190	1279
Battery Load	Displacement(mm)	0.61	1.25	0.86	0.62
	Stress (Mpa)	33	31(28)	30	32
Cargo Frame	Mass (kg)	25.24	8.68	9.02	9.55
	Relative Mass Reduction (%)		65.61	64.26	62.16

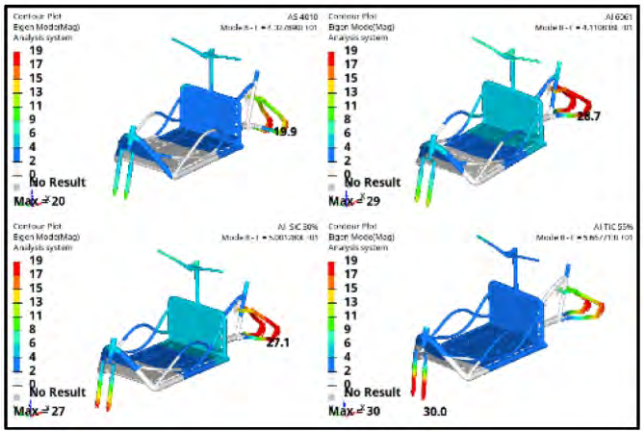

Fig. 4 Bending Mode from Modal Analysis

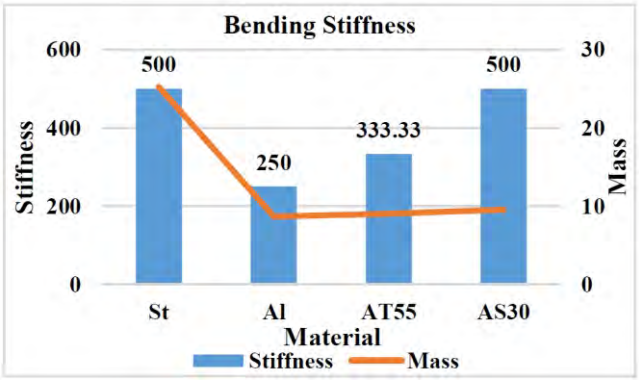

Fig. 6 Bending Stiffness

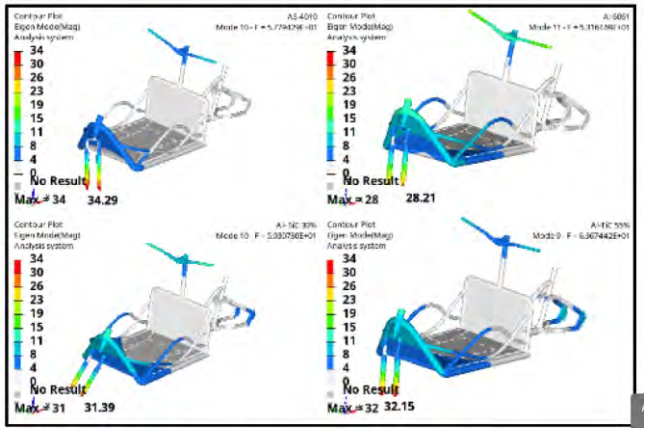

Fig. 5 Torsional Mode from Modal Analysis

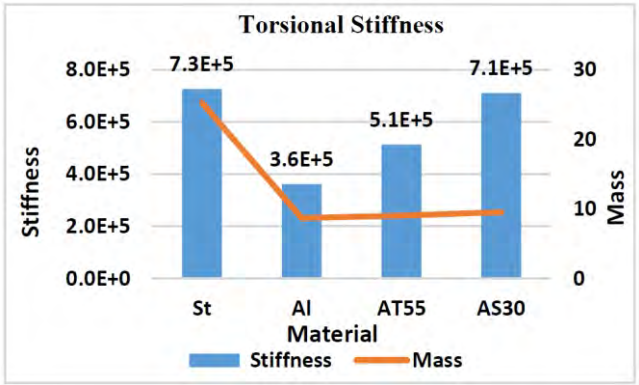

Fig. 7 Torsional Stiffness

VI. CONCLUSION

Finite Element Analysis (FEA) is a practical means to determine the strength and stiffness criteria of the Cargo frame of varying profiles of cross section and transverse member thicknesses. Static and Modal analysis was performed on cargo frame made of baseline material AS4010 and composites Al359-SiC 30% and Al 2024-TiC55%.

- The present study will undergo material selection assessment by developing a weightage score sheet for the selected number of composite materials available for automotive sectors through evaluation of performance, weight reduction, availability, cost, scalability and recyclability.
- In the present study carried out Aluminium composite with TiC 55% achieved a reduction of 62% having the same performance as established by the baseline steel AS 4010.
- But a comprehensive study with selected material with change in profile section is considered to achieve a systematic weightage score sheet of the composite materials for lightweighting automotive parts.

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Digital Framework for Indigenous Fighter Aircraft Development & Sustenance

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Abstract - Siemens' Tool Cost Management solution helps the tool manufacturers and buyers to calculate realistic costs and avoid miscalculations by enabling a parametric calculation of various tool technologies such as injection molding, high pressure die-casting, progressive die stamping, laser cutting, and others. With tool cost management, tool makers and buyers improve business processes and avoid inaccurate cost estimations which can result in unwanted lengthy delivery time and even loss.

Keywords - Tool Cost Management, parametric cost calculation, injection molding die-casting, machining, labor rate.

I. INTRODUCTION

Global procurement markets and increasing cost pressures require professional cost management in the field of molds and tools. Shorter lifecycles paired with higher product variability mean that the share of tool costs in relation to the total costs of a product line is steadily increasing. Therefore the tool costs become a critical focus of cost management – both in tool and mold making and in tool purchasing.

Due to margin pressure, tool costs are an important foundation for the success of products – in the quotation of costs and in the purchase price analysis of tools. It is increasingly important to have detailed and reliable information on tool costs in the early stages of product development. Due to the increasing complexity of tools and smaller production runs, this balancing act is a challenge even for experienced tool specialists, and succeeds only with the help of a powerful cost calculation system that delivers faster, more accurate and comprehensible results based on parametric models.

II. SOLUTION OVERVIEW

The Teamcenter® software for Tool Costing[1] helps you in creating accurate tool cost calculations in less time, with detailed cost breakdowns. You can easily manage tool versions and changes, and you can secure the calculation knowledge within the company. These capabilities are a significant improvement over the disconnected solutions still in widespread use.

Siemen's Tool Cost Management (TCM) solution is built with these salient features:

- Supports all major tool technologies: injection molding, die casting, progressive dies and laser cutting as shown in Figure.1.
- Parametric 3D-feature extraction
- Flexible cost calculations and individual reports as depicted in Figure.2.
- Company-wide knowledge management on a

centralized platform
- Import and export of cost breakdown sheets
- Multiple tool profiles for various business scenarios
- Master reference data based on multiple factors like geographical locations, labor rates, machine details, etc.

Figure 1. Major tool technologies supported by TCM

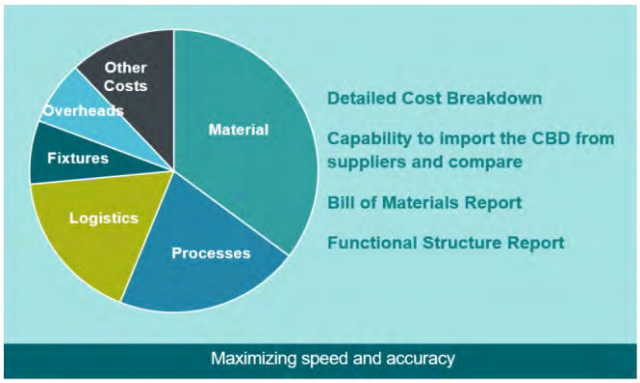

Figure 2 Tool Cost Breakdown structure

III. TEAMCNETER TOOL COST MANAGEMENT

A. Imperative for Tool Cost Mangement solution

TCM is a software-driven methodology that helps Tool designers and manufacturers to understand the cost implications of their design and sourcing decisions. This visibility allows them to identify cost saving ideas such as change in design, simplifying designs, or changing making locations. TCM is a detail-oriented process that systematically determines the "should cost" of the tool.

It develops high fidelity cost models based on the detailed manufacturing process involved to manufacture the tool along with its Bill of Material (BOM). The BOM includes detailed labor, equipment, tooling, setup, material, processes involved in production of tool, including the time and cost for designing the tool. Modeling multiple production methods allows manufacturers to analyze multiple scenarios and perform "what if" analysis.

B. Design for Optimal Cost

TCM allows manufacturers to design and manufacture optimal cost of the tool by providing them feedback on the cost impact of their decisions. This approach is often more effective than "value engineering" processes that aim to take out cost from in-market products. **Reducing cost is more feasible early in the design process where flexibility is at the highest point before decisions are locked in.**

C. Cost Engineering

Designing a tool for ideal cost is only part of the battle. Most manufacturers rely on their supply chain for components and assemblies. To compete profitably, then, they need to find the right suppliers and negotiate a fair price. **Requests for Quotation (RFQs) aren't effective at reducing prices because they only allow price competition and not competition based on cost.** "Most purchasing organization only do market requests and compare them, they don't know the details," says the equipment manufacturer. Pricing is a commercial issue. For example, suppliers might be able to command premiums for innovation or unique capabilities. But cost is factual.

Using knowledge and costing models, manufacturers can simulate their suppliers' production costs to develop a should cost. Although it's likely no supplier that can match an ideal should cost model with existing capabilities, it provides purchasing with the knowledge needed to help get the best supplier pricing. **It helps you to find out how suppliers are doing the work and where they are anchoring higher cost[2]. The price should include a reasonable ROI/IRR for the supplier** because it's important that it's win-win to keep them financially healthy while remaining aggressive on cost reduction.

PCM changes negotiations from battle of wills to battle of knowledge.

D. Drive Continuous Cost Improvement in the Supply Chain

The goal should be to cut down supplier cost not just beat them up on price and potentially force them into selling bad business. In the long run that is not good for anyone. **TCM can help identify supplier inefficiencies and put in place a plan to close the gap between their cost and should cost.** This is valuable for contract negotiations but also for continuous improvement. It helps you to have detailed discussion with supplier on their offers and where it deviates from the best practice.

Manufacturers and suppliers can share in the benefits of TCM. **The problem isn't that designers or suppliers don't want to reduce the cost,** they don't know where to reduce the cost. TCM helps in bringing transparency. Manufacturers can partner with their suppliers to reduce cost from the supply chain. It's good for a supplier to see where they have some disadvantages compared to their competitors. **TCM can help manufacturers develop their suppliers, for example setting up Six Sigma and Kaizen projects to continuously improve and drive additional cost savings.** Suppliers can also leverage TCM processes and software directly to develop more accurate quotes and defend costs with their customers.

It helps you in predicting the cost at early stages of design as shown in Figure 3.

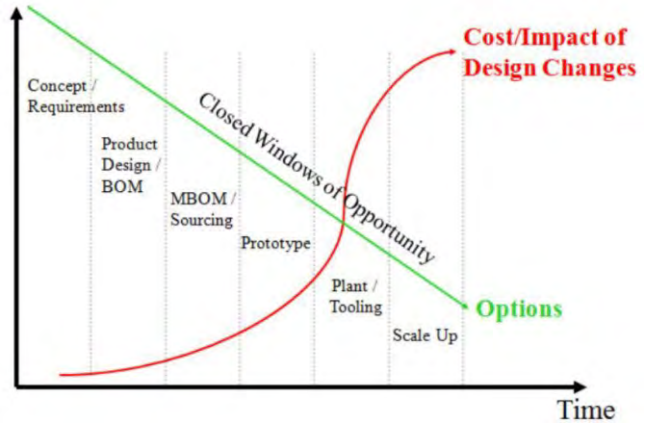

Figure 3. Graph depicting Cost Impact with Design Changes with Time

E. Centralize Database with reference master data

TCM comes with inbuilt master reference data with detailed list of major operations and processes along with the material cost, labour cost, etc., based on several factors like geographic location, quantity, etc. across the globe.

User can reference master data provided or can create his own reference data as per the business needs.

F. Process of using Tool Cost Management

The process of Tool cost calculation follow with below process flow.

a) Selection of Tool Technology
b) Feature extraction from part geometry
c) Tool profile selection
d) Detail Tool cost breakdown

TCM support selection the various tool technology like Injection moulding, Die Casting, Forging or Sheet Metal with support of all technical parameter and formula inbuild in TCM. After import of tool technology it can extract feature like undercuts, ribs etc directly from CAD data if available to the application. CAD part feature are automatically identifies likes undercuts, sections, bosses, ribs, insert areas along with the dimensions and volume. Those features are also classified as high, medium or simple complexity based on geometric and surfaces. This impact the over tool cost when calculated by TCM. Figure 4 shows automatic feature extraction from CAD geometric. All features can also be filled manually or modified during extraction in the tools.

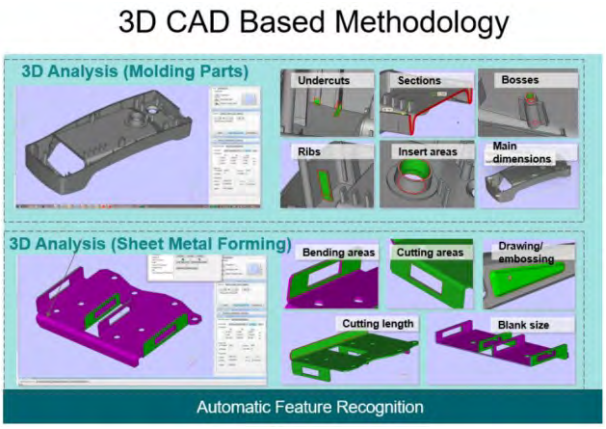

Figure 4 Automatic Feature Recognition

G. Tool profile selection

Tool profile selection which defined overall Bill of material of all components of tools along with all operations and other cost factor. It is template-based approach where tool profiles incorporate all aspect of manufacturing process which required to manufacture tools. For example, it will have detail of machining with machine for hot chamber or cold chamber, Design and Simulation effort, Material type for various component of tool. Siemens TCM provides out of box tool profiles with standard process definition which has been incorporated based on various data and experience of various tool manufacturer globally. However, customer can create their own profile by cloning out of box profile or creating from scratch.

Tool profile based on geometric parameter and feature definition create overall estimate in term of quantity of material, machine hours as well design efforts automatically. For example, TCM selects required operations along with available machines in TCM and calculates the machine hours for every process. Figure 5 shows milling operation calculation. It provides complete bill of material along with detail of manufacturing process for all parts.

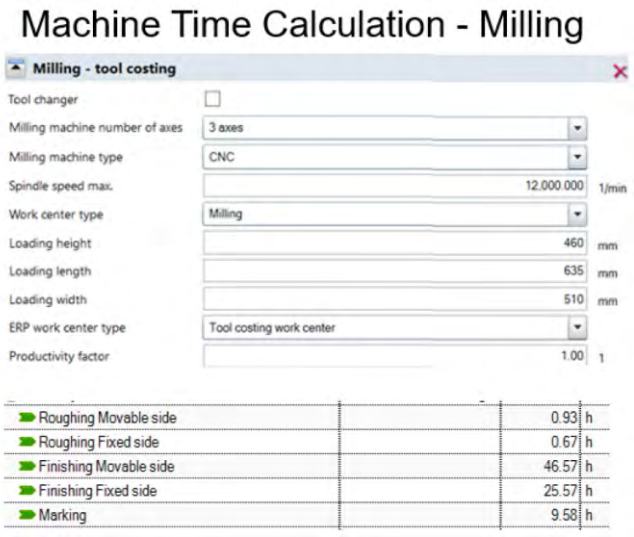

Figure 5 Milling Machine Hours

Overall cost is calculated based on selected site/location for manufacturing tool. This enable TCM to take unit cost of labour, machine hour rate, material prices based on those geographical areas. Figure 6 shows cost break down along with bill of material. This also help is creating various what if scenario based of selecting different geographical location as well different tool profiles (for alternate manufacture process). Figure 7 shows all component of tools along with different tool profile and location scenario

Designation	Procurement type	Quantity	Quantity unit	Costs	Currency
V0_1	Purchase	1.00	Pcs	2,566,337.29	INR
Basic design	In-House Manufacturing	1.00	Pcs	249,974.93	INR
Cavity plates and...	In-House Manufacturing	1.00	Pcs	117,227.88	INR
Mold plate nozzle...	In-House Manufacturing	1.00	Pcs	60,614.49	INR
Mold plate ejector...	In-House Manufacturing	1.00	Pcs	56,264.97	INR
Milling Centering		0.14	h	348.41	INR
Standards and base...	In-House Manufacturing	1.00	Pcs	132,747.06	INR
Die cavity	In-House Manufacturing	1.00	Pcs	1,279,163.02	INR
Basic processing...	In-House Manufacturing	1.00	Pcs	80,626.62	INR
Cores processing...	In-House Manufacturing	1.00	Pcs	1,160,888.84	INR
EDM processing costs	In-House Manufacturing	1.00	Pcs	37,647.57	INR
Basic functional units	In-House Manufacturing	1.00	Pcs	414,329.13	INR
Sprue system	In-House Manufacturing	1.00	Pcs	297,592.87	INR
Ejector system	In-House Manufacturing	1.00	Pcs	91,775.70	INR
Water lines	In-House Manufacturing	1.00	Pcs	24,960.56	INR
Special functional units	In-House Manufacturing	1.00	Pcs	96,497.75	INR
Slide mold	In-House Manufacturing	1.00	Pcs	96,497.75	INR
Design / NC programming	In-House Manufacturing	1.00	Pcs	404,165.93	INR
Design		161.93	h	195,243.02	INR
CAM and NC-...		116.72	h	137,722.90	INR
Mold flow simulation			s	71,200.00	INR

Figure 6 Bill of Material with Cost Break down

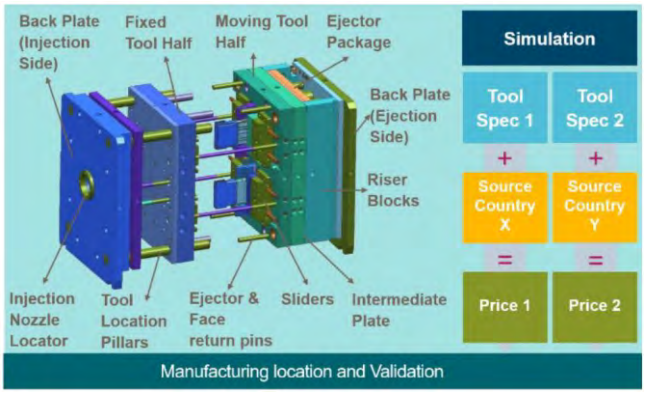

Figure 7 Tool Cost scenario

H. Detailed Cost Break Down

TCM provides complete BOM of tool along with the cost which helps in better understanding of cost break down. Various Cost breakdown reports provide insight of cost component and their impact on overall cost of the tools. For example, figure 8 provide cost machining cost breakdown detail across all process and figure 9 provide functional cost break down based on function like Assembly, Die cavity etc. Reports can also be exported in excel for further analysis or sending internally or external stake holders.

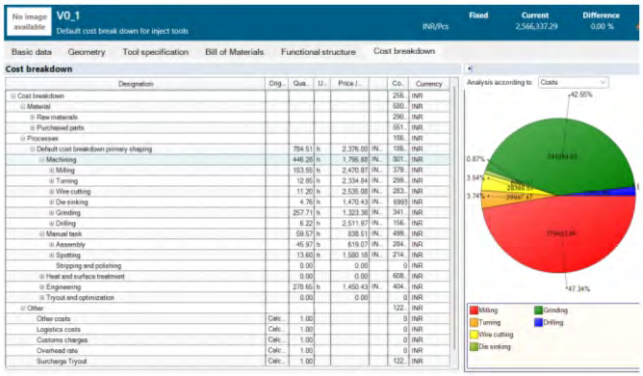

Figure 8 Machining Cost Breakdown

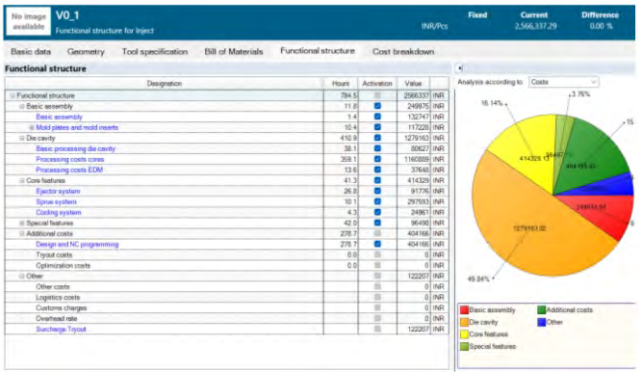

Figure 9 Functional Cost Breakdown

I. Benefits

Siemens Tool Cost Management provides various benefits which help enterprise to get tool cost accurately and quickly. Below are some key benefits of Tool cost management

a) Standardization: through knowledge reuse by standard tool profiles and standard reference data for material price and machine hour rates.
b) Collaboration: Centralize database and integration with PLM and ERP systems
c) Accuracy: Cost calculation is accurate based on latest material prices and accurate machine hours calculation.
d) Efficiency: Reduce efforts from hours or days to few minutes. Reduce dependency of skill people to standard tool profiles.

Tool buyer can better negotiate with suppliers. Tool manufacturer will have better insight of tool cost factors which can help them to optimize cost based on alternate selection of process, geographical location or material.

Figure 10 shows overall benefits using Siemens Tool cost solution.J.

Figure 10 TCM Benefits

Summary

Siemens tool cost management provides immense opportunity to both tool buyers and manufacturer to estimate cost more accurately and scientifically in much lesser times. This will help in transparency of cost quotation resulting cost saving for tool buyer as well more accurate predict profit margin for manufacturer. Buyers can do better cost negotiation based on comparing cost quoted by supplier to those provided by tools. This will help in better price negotiation. Cost Breakdown report and compare reports can give more insight of the cost factors which can help in optimization of cost based on alternate selection of process, geographical locations, or materials.

K. Abbrivation

CBD	Cost Breakdown
MHR	Machine Hour Rates
TCM	Tool cost Management

References:

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Comparison of inspection process between laser based scanner and CMM for MBD aircraft structural parts

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Abstract - Model based definition (MBD) and DFMA (Design for Manufacturing and Assembly) introduced in design of aircraft structure components to reduce cycle time and cost. Aircraft fuselage and wings structure outer surface components following specific aerodynamic profile. Recent design and FEM (finite element methods) analysis optimization leads to complex shape of aircraft structural components. Model based definition (MBD) provides product manufacturing information (PMI) data to fabricate components like GD &T parameter, Specific aerodynamic profile requirement, type of fabrication process, required surface finish, material related information etc. For machined component suitable CNC program were made from MBD CAD model using CATIA software and component fabricated on 5 axis CNC machine using standard Al alloy mentioned in PMI data. Now biggest requirement is to validate the component. The component was inspected on both non-contact LASER based scanner and contact probe based fixed head coordinate measuring machine (CMM). Major challenge faced during dimensional verification of component. (a) Position of pilot hole present on aerodynamic profile of the component. (b) Aerodynamic profile of the component. (c) GD & T Parameter. In this paper the investigation and comparison were performed between dimensional inspection process of component by LASER scanner and Coordinate measuring machine (CMM). It is observed that inspection by LASER scanner provide more flexibility with dimensional accuracy. Inspection of pilot hole on aerodynamic profile, aerodynamic profile of component and GD &T parameter verification is more challenging and time consuming in CMM machine and all these checks are easy and less time consuming in portable LASER scanner for given metallic material. Dimensional accuracy is a little better in CMM machine. Both inspection process required clean and dust free environment

Keywords - Aerodynamic profile, CMM, Dimensional inspection, DFMA, Laser Scanner, MBD, PMI Data, GD & T

I. INTRODUCTION

We have adopted Model-Based Definition (MBD) and Design for Manufacturing and Assembly (DFMA) in Design and manufacturing for improve our production and reduce cost. Model-Based Definition (MBD) is being adopted by the manufacturing industry as a single source for all product information in place of conventional 2D drawings. Applications of MBD are categorized into seven domains. These domains are lifecycle information; design, discrete part manufacturing, and inspection; assembly; maintenance, repair, and overhaul; process planning; engineering change management; and contemporary aspects of digital product definition [4]. Continuous improvement and

optimization of products, which is the most often reflected in more complex geometrical and dimensional characteristics of products and increasing market demands for quality, lead to the development of new solutions in quality control. In industry today, the control of geometric characteristics is most often performed by the tactile method of probe stylus, i.e. using 3D coordinate measuring machines (CMM). Coordinate measuring machines have long been the only option in quality control of various products and have become generally accepted in industrial quality. In recent years, the development of digital technologies, i.e. the development of a new generation of hardware and software, has enabled the development of other methods of 3D measurement such as 3D scanner, which has proven to be a good alternative to CMM machines.

With the development of technology, there has been a revolution in production. Increasing the capabilities of machines has led to an increase in demand for functional and aesthetic properties of products on the market. Also, increased competition in the market has led to the optimization of product performance, which has resulted in increased requirements for the accuracy of manufacturing parts and reducing the allowable tolerances of products [6]. New airplane Develop system based on 3D digital technique and multi-companies cooperating develop mode is formed, and it is successfully applied in the large aircraft development, and it has been proved that the design period of the product is shortened by more than 40%. The technique system can be applied to the aeronautics, the astronautics, the large ship, and the other manufacture domain [5]. Aiming to eliminate counterproductive data formats and collaboration methods used in the industry, the proposed method uses an MBD 3D PDF-based template as the main source of the necessary information for all the product life-cycle processes. This lightweight template file, in cooperation with the PDM software, provides the ability to all the departments to obtain the required information, and contribute to the generation of them through a proposed workflow [3]. After design and fabrication of physical product the validation is required.

A 3D scanner is a non-contact, non-destructive digital device that uses a light line/laser to accurately capture the shape of a physical object into Computer-Aided Design (CAD) data. It generates a point cloud or a set of data points in a coordinate system that accurately depicts a physical object's size and shape. The urge of human beings to build and recreate 3D objects is an essential requirement in the context of Industry 4.0[2]. Currently, a CMM (coordinate measuring machine) and a three-dimensional (3D) laser scanner are widely used in the fields for shape reverse engineering and quality inspection. CMMs use a trigger-type probe and analogue scanning probe. The trigger-type CMM acquires point data by touching the probe to the part, such that it is appropriate for measuring primitive features that need small number of point data. The scanning-type CMMs can capture more sampling points than the touch trigger-type and have better accuracy than vision sensors. They can be used for measuring freeform features. Laser scanners, on the other hand, can obtain a large amount of point data by non-contact method in a short time. Since the accuracy of the laser scanner is getting improved, they are widely adopted for many applications in industry

2. ANALYSIS

Requirement is to verify component fast and accurately, all GD &T parameter provided in the 3D PDF as per model based definition(MBD) PMI data and pilot hole position on the both aerodynamic profile and other planer surface as per DFMA. Various method of inspection studied. CNC program were made from MBD CAD model using CATIA software and Test components fabricated on 5 axis CNC machine using standard Al alloy mentioned in PMI data and dimensionally inspected by various method like LASER Scanner, fixed head CMM.

2.1 Product Manufacturing Information (PMI)

Product manufacturing information (PMI) data provide information which help to manufacture the component like GD &T parameter, Specific aerodynamic profile requirement, type of fabrication process, required surface finish, material related information etc. Some latest CMM and

LASER scanner software like PCDMIS, Polyworks and GOM inspect etc. are able to read Product Manufacturing Information (PMI) data directly from MBD CAD model

2.2 Dimensional inspection of component by CMM and Comparison with MBD CAD model

LITZ CMM machine used for dimensional inspection of component, size of CMM machine is 1000x1200x600 mm component were clamped on CMM machine bed, CMM program were made using PCDMIS software temperature of inspection area maintained 25 0C Component outer surface profile, all GD & T parameter, pilot hole position inspected and compared with CAD model.

2.2.1 Full CAD model comparison with physical part scan.

This feature not available in CMM machine.

2.2.2 Other GD & T parameter comparison

Table 1 represents GD & T parameter required by design compared with measured values by CMM

2.2.3 Position of Pilot hole on aerodynamic profile

TABLE 1

	Nominal value	Measured value
Flatness of bottom plan Datum A	0.2	0.14
Position of tooling hole 1 Datum B	0.1	0.044
Position of tooling hole 2 Datum C	0.1	0.0285
Profile with respective A B C	0.2	0.11
Distance between both tooling hole	x	x.03

comparison

The challenges faced for verification of pilot hole position (a) vector and point only available as per DFMA in CAD model (physical pilot hole not available in the CAD model) so can't be verify with program that's by checked manually operating CMM machine (b) the Diameter of pilot hole is 2.5 mm so dependency on either 1 mm diameter probe or external pin to be put in pilot hole for measurement which may lead to additional operator error. Minimum 3d distance between each Pilot hole determined by measuring each pilot hole as circle and projected on nearest locally created plan by manually operating CMM machine and in MBD CAD model minimum 3d distance checked between each vector point, deviation found 0.9 mm to 1.3 mm. Time taken only in this process was 6 hours. Figure 1 shows some pilot hole measured by CMM on aerodynamic profile

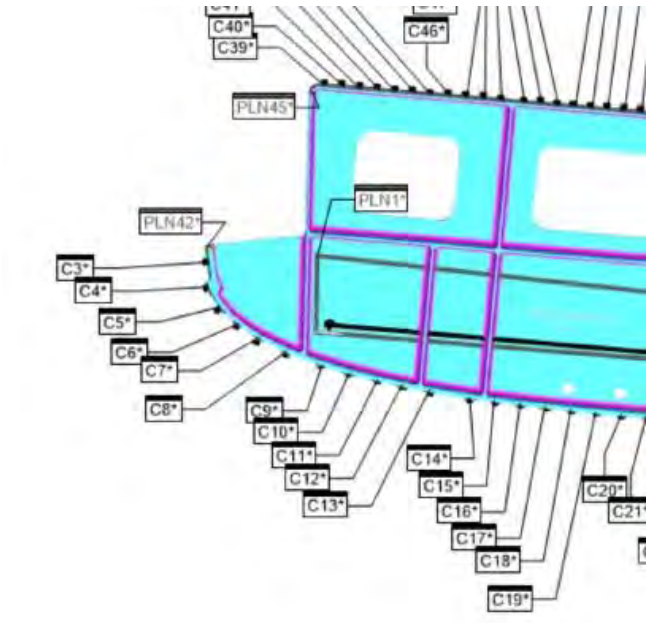

Figure 1

2.3-Dimensional inspection of component by LASER scanner and Comparison with MBD CAD model

ZEISS T-SCAN hawk 2, 3d LASER scanner used to scan the machined component temperature of inspection area maintained 25 0C since material of component is AL alloy and surface roughness maintained Ra 0.8 µm or less which found reflective surface this is the limitation of 3d scanner to avoid reflection developer applied and also lights switched off for better scan data. The component dimensionally inspected by GOM inspect software, component aerodynamic outer surface profile, all GD & T parameter inspected and compared with CAD model. For pilot hole position, pilot hole in the component scanned and compared with vector and point available as per DFMA

2.3.1 Full CAD model comparison with physical part scan

Component scanned and superimposes on MBD CAD model the deviation in desired area of component given. Maximum deviation is +0.550 mm and minimum deviation is -0.017 mm as shown in figure 2.

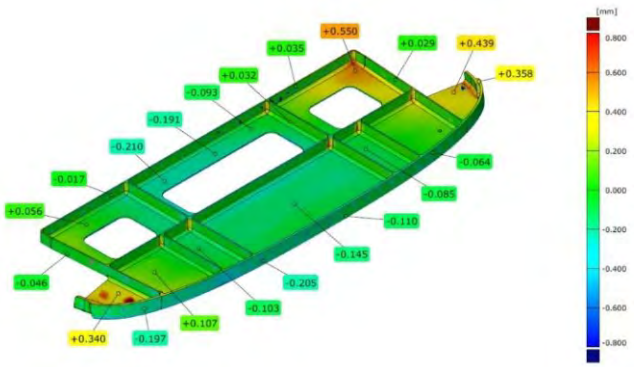

Figure 2
(Typical example of CAD compare of sample part)

2.3.2 Other GD & T parameter comparison

Table 2 represents GD & T parameter required by design compared with measured values by 3d Scanner

TABLE 2

	Nominal value	Measured value
Flatness of bottom plan Datum A	0.2	0.2
Position of tooling hole 1 Datum B	0.1	0.04
Position of tooling hole 2 Datum C	0.1	0.05
Profile with respective A B C	0.2	0.19
Distance between both tooling hole	x	x.09

2.3.3 Position of Pilot hole comparison

Pilot hole on the component scanned by 3d laser scanner and compared with vectors and vector point maximum deviation was 0.3 mm time taken in this process was 30 minute while total time taken by 3d scanner for overall inspection is 1 hour

2.4 Comparison between Dimensional inspection of component by 3d LASER scanner and CMM

2.4.1 Full CAD model comparison with physical part scan

With the help of this feature of 3d laser scanner, any complex shape of component (might be required by recent design and optimization) can be verified easily and accurately any dimension which is didn't even asked by the design department could be verified faster. Figure 2 determines the comparison between overall scanned data by the 3d LASER Scanner with the MBD CAD model, the deviation explained in the color code, but this over all comparison feature of scanned data with the MBD CAD model is not available in CMM inspection.

2.4.2 Other GD & T parameter comparison

Table 3 represents GD & T parameter measured values by 3d LASER Scanner compared with measured values by CMM

TABLE 3

	Measured value by 3d Scanner	Measured value by CMM
Flatness of bottom plan Datum A	0.2	0.14
Position of tooling hole 1 Datum B	0.04	0.044
Position of tooling hole 2 Datum C	0.05	0.0285
Profile with respective A B C	0.19	0.11
Distance between both tooling hole	0.09	0.03

2.4.3 Position of Pilot hole comparison

The inspection The position of pilot hole on aerodynamic profile with CMM following procedure that first creating nearest local plan on the surface and project probed circle on that plan may create operator error so that's by the maximum deviation might be 1.3 mm which is beyond the tolerance while the position of pilot hole on aerodynamic surface with 3d laser scanner is 0.3 mm. The time taken by CMM is approximately 12 times more than 3d scanner.

2.5 Inspection Reporting

Both inspection methods are able to provide desired type of PDF inspection report

3. RESULT AND DISCUSSION

3d laser scanner inspection is faster, cost effective, accurate and safe, working on non-contact optical technology while CMM inspection requires more operator skill.

In 3d laser scanner full scanned surface with CAD model comparison possible which leads to verify any type of complex shape of component and also cannot miss any surface area which is not asked by Design this is the great advantage over CMM which leads to better quality parts in the Aircraft.

LASER based portable 3d scanner provide Verification of position of pilot hole on aerodynamic profile faster and with better accuracy while above parameter verification with CMM may add more operator error.

LASER based portable 3d scanner provide Verification Aerodynamic profile and rest all GD & T parameter of metallic machined component with accuracy and highest flexibility in less time. Dimensional inspection from CMM machine provide all above verification with slightly better accuracy

4. CONCLUSION

For Verification of position of pilot hole on aerodynamic profile and on other plan surface, Aerodynamic profile, rest all GD & T parameter of metallic machined component LASER based portable scanner recommended due to its capability to do faster with accuracy. For specific higher accuracy requirement with less feature dimensional inspection like wing attachment bracket, landing gear can be dimensionally inspected with CMM.

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Implementation of Jig-less Assembly Concept for future Combat Aircraft Program

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Abstract - This paper summarizes the outcome of the Technology Development Activity initiated towards implementation of Jigless Assembly for future Combat Aircraft Program. Need and importance of Jigless Assembly concept for aircraft industry was emphasized. In this paper we have covered two assemblies implementing Jigless concept – i) Fabricating a simplified section of Nose Box Assembly with Jigless Assembly Concept and ii) Fabricating a typical Control surface assembly with Jigless Assembly Concept. Jig-less assembly design was elaborated with addition of controlled tolerances to holes on the existing parts and utilizing them for locating/ locking during assembly. Assembly Procedure was also briefed for both the phases considering Jigless assembly. Both the assemblies were successfully assembled meeting all the functional requirements.

This paper proves that a significant amount of Tooling cost can be eliminated by adapting Jigless assembly concept. Also, this concept is flexible to the design changes that are unavoidable during aircraft development phase.

Keywords - Conventional Assembly, Jigless Assembly, Fixture, Assembly Tolerance Requirement, Design for Jigless Assembly, Tolerance Stack-up Analysis, etc.

I. INTRODUCTION

Aircraft Tooling is a critical activity for combat aircraft program. Presently the conventional jigs used for aircraft assembly are extensive structures and requires regular maintenance and calibration. Furthermore, they are product specific and expensive.

What is Jigless?

In conventional design approach for assembly jig, locators are introduced for each part to located and lock it with respect to Jig co-ordinate system. With all the locators, contour plates and Jig frames to support them the Jig becomes an extensive bulky structure. Whereas Jigless is a design concept for assembly jig where the number of Jig elements are greatly reduced. Instead of locating each part precise design features are introduced such that one part can be located with respect to the other. Here, need for extensive tooling is eliminated instead, a minimum holding fixture is required to carry out the assembly.

Need for Jigless Assembly

The present assembly jigs are product specific and any change in the aircraft design needs new tooling. This leads to long lead time for realization, expensive and also large inventory. In addition to that, these tools need regular maintenance and calibration. With these drawbacks there is a need to reduce the number of jig elements and adopt Jigless assembly approach.

2. FABRICATING A SIMPLIFIED SECTION OF NOSE BOX ASSEMBLY WITH JIGLESS CONCEPT

2.1 OBJECTIVE

Objective is to incorporate additional jigless features onto design and fabricate detail parts with fine tolerances and to achieve the final assembly level tolerance requirements.

Towards this, a small section of Nose Box Assembly in Wing was taken and simplified in-terms of manufacturing. The objective is to check the feasibility of manufacturing of detail parts with fine tolerances and check whether the assembly will meet the assembly level requirements.

2.2 ASSEMBLY REQUIREMENT

- Assembly Tolerances: The longitudinal distance of 270mm should be within +0.15mm, transverse distance of 180mm should be within + 0.1mm and height of 67mm should be within + 1mm.
- Product specific jigs should be avoided or minimized while carrying out this assembly
- Weight of the assembly should not be increased (No Design change is allowed)

The assembly level tolerance requirements are described in the Fig.2.2 below:

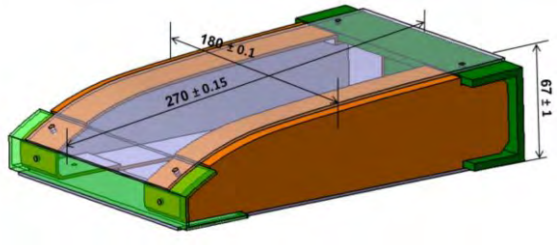


Fig. 2.2 Assembly Requirement

2.3 PARTS DESCRIPTION:

Nomenclature of the parts involved in assembly is shown in Fig.2.3.

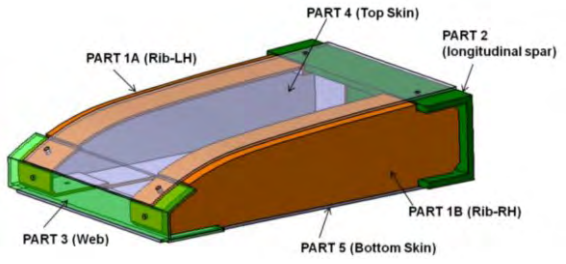


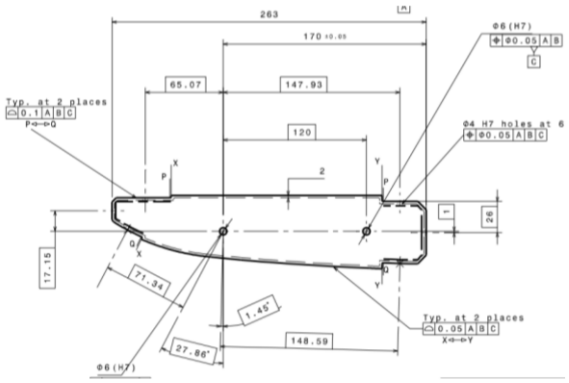
Fig. 2.3 Parts Description

2.4 DESIGN FOR JIGLESS ASSEMBLY

In jigless assembly concept parts are positioned taking reference of other part and locked. To make this possible below mentioned features are introduced in each of the parts:

a) Two locating holes with precise diametrical and positional tolerances. This would help is positioning of one part with respect to the other.
b) Remaining pilot holes are introduced so that they can be opened out and riveted later.

Once the parts are designed and features are added in order to achieve jigless assembly 2D manufacturing drawings are produced. Special care is taken in introducing the part level profile and hole tolerances. One typical example of 2D manufacturing drawing is shown in Fig. 2.4 below:



2.5 ASSEMBLY SEQUENCE/ PROCEDURE

The brief assembly sequence /Procedure (for reference) is mentioned in the below Table2.5.

Table2.5
Assembly Sequence/ Procedure

Sl. No.	Sequence	Description
Step-1:	Locking Bottom Skin (Part 5) to the fixture.	The fixture should have 2 integrated locking pins diagonally placed to lock the skin at 2 locating holes. It should also have provision to pass on holes from the skin to the Rib.
Step-2:	Locating the Web (Part 3) and Longitudinal Spar (Part 2) on the Bottom Skin	The Web and the Longitudinal Spar should be located on the Bottom Skin by means of 2 locating holes each. Provision should be there on the fixture to pass on holes from Skin to the Web and Longitudinal Spar.
Step-3:	Bringing both the LH and RH Ribs from lateral sides of the Assembly	Both the LH and RH Ribs are to be brought from lateral sides and located on the Web and Longitudinal Spar by means of 2 locating holes each.

Sl. No.	Sequence	Description
Step-4:	Locating the Top Skin and completing the Final Assembly	The Top Skin is to be brought and located on the Web and Longitudinal Spar at 2 diagonal locating holes. Holes are to be passed on from Top Skin to the Ribs. All the temporary locking has to be replaced with permanent rivets.
Step-5:	Inspection check - Assembly level	Inspection check for dimensional and geometrical tolerances of the assembly

2.6 REALIZATION OF ASSEMBLY

Enquiry was floated. Alpha Tocol was selected as the vendor for manufacturing of the assembly. Fabrication of the parts and assembly according to the said sequence was done by them. A picture of the finished assembly is shown in Fig.2.6 below:

Fig. 2.6 Actual Assembly

Dimensional inspection was carried out. The dimensional tolerance was achieved within 20 micron and profile tolerance was achieved within 50 microns. So, the assembly level tolerance requirements were well met. So, we proceeded for the next assembly.

3. FABRICATING A TYPICAL CONTROL SURFACE ASSEMBLY WITH JIGLESS CONCEPT

3.1 OBJECTIVE

Objective is to prove out the assembly of a typical control surface to the required assembly tolerances with incorporation of additional jigless features onto design at part level. This will enable the assembly operations without utilizing the traditional jig.

Towards this, existing rivet holes were used for carrying the assembly operations. The concept was to control the tolerances of these rivet holes on the existing parts and utilizing them for locating/ locking during assembly.

3.2 ASSEMBLY REQUIREMENTS:

- Assembly Tolerances: The longitudinal distance of 1433.12mm should be within +0.2mm, the transverse distance (x) should be within +0.2mm and the height variation (h) should be within + 1mm.
- Contour Tolerances: The external contour tolerances shall be within + 1mm.
- Product specific jigs should be avoided or minimized while carrying out this assembly.
- Weight of the assembly should not be increased (No Design change is allowed).

The assembly requirements are described in Fig.3.2 below:

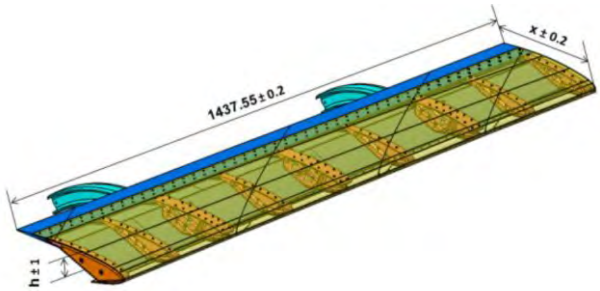


Fig.3.2 Assy requirement for typical control surface

3.3 PARTS DESCRIPTION

Nomenclature of the parts involved in assembly is shown in Fig.3.3.

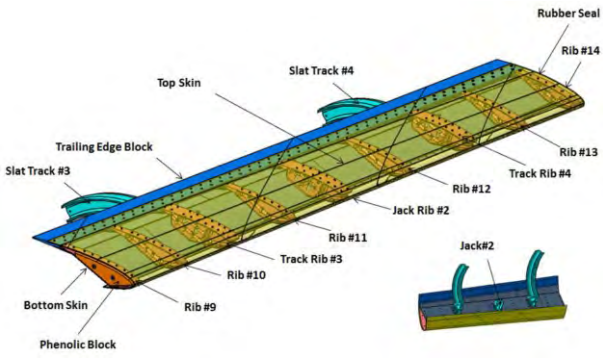


Fig.3.2 Assy requirement for typical control surface

3.4 DESIGN FOR JIGLESS ASSEMBLY

In jigless assembly concept parts are positioned taking reference of other part and locked. To make this possible below mentioned features are introduced in each of the parts:

a) Two locating holes with precise diametrical positional tolerance. This would help is positioning of one part with respect to other.
b) Remaining pilot holes are introduced so that they can be opened out and riveted at later stage.

In addition to this a fixture is designed to locate and lock all the ICY (Interchangeable) points and check the overall dimensions which needs to be controlled as part of assembly requirements.

Once the parts are designed and features are added in order to achieve jigless assembly 2D manufacturing drawings are produced. Special care is taken while introducing the part level profile and hole tolerances.

3.5 ASSEMBLY SEQUENCE/ PROCEDURE

The brief assembly sequence /Procedure (for reference) is mentioned in the below Table3.4.

Table3.4
Assembly Sequence/ Procedure

Sl. No.	Sequence	Description
Step-1:	Bottom Skin locked to the fixture.	Bottom Skin is temporarily located at 2 places with locators by locating pins.
Step-2:	Trailing Edge (T.E.) Block brought	T.E. Block is temporarily locked at 2 places by the locating pins. Final size holes are passed from T.E. Block to Bottom skin
Step-3:	Ribs brought on the assembly.	Rib #14 and Rib #9 brought onto fixture and locked at 2 tooling holes each. Rib #14 and Rib #9 temporarily located on Bottom skin at 2 places by wedge locks. Similarly, Ribs at other stations are brought and temporarily located. Final size holes are passed from Rib to Bottom Skin.
Step-4:	Riveting done for Ribs to Bottom Skin and anchor nuts riveted on Track and Jack ribs.	Riveting is done for Ribs to Bottom Skin. Drilling is done on Track and Jack Ribs for anchor nut rivet holes and anchor nut is riveted on Track and Jack ribs.
Step-5:	Holes passed from Phenolic Block to Rib #9& anchor nut is riveted at those holes.	Phenolic Block is positioned on Rib #9 and holes are transferred from Block to Rib. Anchor nut rivet hole is drilled on the Rib and anchor nut is riveted onto Rib #9
Step-6:	Holes passed from Rubber Seal assy. to Rib #14 & anchor nut is riveted at those holes.	Rubber Seal assy. is positioned on Rib #14 and holes are transferred from Rubber Seal assy. to Rib. Anchor nut rivet hole is drilled on the Rib and anchor nut is riveted onto Rib #14
Step-7:	Top Skin brought and riveted to T.E Block, Ribs & Bottom Skin.	Top Skin located by the 2 locating pins. Final size hole passed from top skin to T.E Block, Ribs & Bottom Skin. Riveting done for all the holes.
Step-8:	Phenolic Block fastened to Rib #9.	Phenolic Block is brought and positioned on Rib #9. It is fastened to Rib #9 using DIN Screw.
Step-9:	Rubber Seal Assy. fastened to Rib #14.	Rubber Seal Assy. is brought and positioned on Rib #14. It is fastened to Rib #14 using DIN Screw.
Step-10:	Tracks and Jacks fastened to Slat Assy.	Tracks and Jacks are loaded and located on assy. They are fastened to Slat using DIN Screw and spanner at respective positions.

3.6 REALIZATION OF ASSEMBLY AND FINAL INSPECTION

Fabrication of the parts and assembly according to the said sequence was done by Alpha Tocol. The completed assembly picture is shown in Fig.3.6 below.

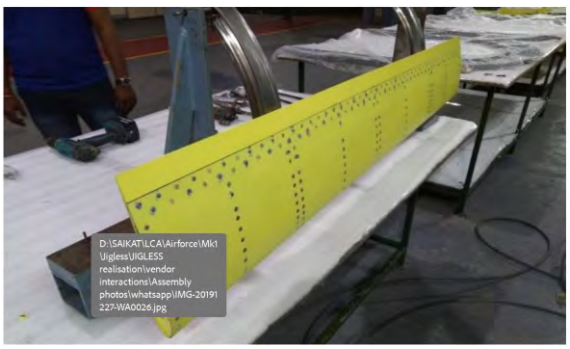


Fig. 3.6 Completed Assembly mounted on the fixture

Tolerance of ICY points are achieved within 80 microns positional tolerance and profile tolerance

for the assembly was achieve within 0.6 mm. The results are meeting our assembly tolerance requirement.

4. CONCLUSION

The CMM inspection results prove that Jigless Assembly is achievable with assembly tolerance meeting the assembly requirement. In the above concepts we have used the existing rivet holes as the jigless features by introducing tolerances to it. So, we have not incurred any increase in manufacturing cost due to addition of extra features. Furthermore, a lot of time and money can be saved in conventional jig design and maintenance. Jigless Assembly concept doesn't require the need of hand layout method during assembly phase for drilling rivet holes and thus removing the scope of human error. It increases the ease of assembly with a simple fixture. During the process of assembly in the shop floor a lot of lessons were learnt and that knowledge can be used in improving the fixture further.

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Design and development of an airborne Cold plate through vacuum brazing technique

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Abstract / Executive Summary - Electronic units used in aircraft, are called as avionics. They are packaged appropriately in box-like structures so that they are easily replaceable and hence are called Line Replaceable Units (LRUs). Radar electronics having high power densities need to be cooled to keep the temperatures within limits for reliable operations. In the indirect liquid cooling of these electronics, a heat sink is required that acts as an interface between the LRUs and the coolant. Hence design of a cold plate that acts as a heat sink has become essential that meets the cooling requirements. To be airborne, the cold plate must be compact, easy to integrate, and need to undergo all the qualification tests as per standards. For the avionics rack, having three rows of LRUs, a cold plate of dimension 1.8m x 0.24mx 0.012m need to be designed and developed. Realization of such a lengthy, 12mm thick cold plate and maintaining the surface planarity through the vacuum brazing technique is quite challenging. After failures, the process to get the desired final thickness of 12mm cold plate is established. Cold plates are realised like LRUs and thermal performance is evaluated. Vibration, acceleration and shock tests are performed on the cold plate and found to be satisfactory. Details are presented in this paper.

Keywords - Avionics rack, cold plate, vacuum brazing, acceleration, vibration

I. INTRODUCTION

A radar typically consists of digital Airborne Active Electronically Scanned Array (AESA) antennae. Figure 1 shows the antenna and the supporting electronics of an airborne radar. During the radar operations, these electronic units (LRUs) generate large amounts of heat. To keep the device temperature of the LRUs within the permissible operating limits, indirect liquid cooling is resorted to [1,2].

In order to transfer the generated heat from LRU to the liquid, a heat transfer medium in the form of a heat sink is required. Hence a cold plate design has become essential. To effectively accommodate the specified number of LRUs, they need to be arranged vertically forming three rows. Hence, the LRUs need to be butted to the heat sinks called cold plates which are liquid-cooled and to be mounted inside the avionics racks. These racks are designed with stringent weight and volume constraints and have provisions to accommodate the ducts (or tubes) for cooling. Keeping in view of spatial requirements, the cold plate size needs to be limited to 1.8m x 0.24mx 0.012m.

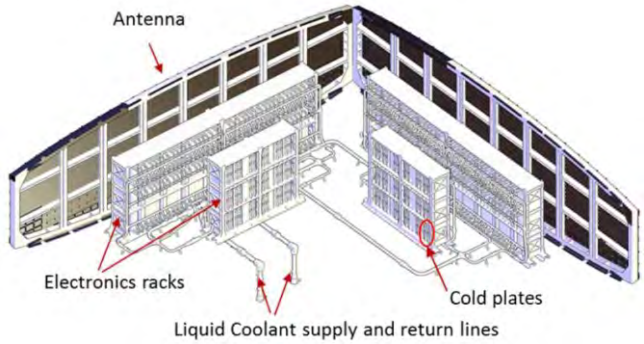

Figure-I A view of the antenna with supporting liquid-cooled electronics racks

Also, to be a good heat sink, the cold plate must be of lightweight and possess good thermal conductivity. It must be hollow to allow coolant circulation through it with the necessary provisions of inlet and outlet. It must have a necessary area to enhance heat transfer. Most importantly, the joint of cold plates must be leakproof.

II. METHODOLOGY

To meet the criteria as discussed in the introduction, Aluminum alloy Al 6061, is chosen as it has good thermal conductivity compared to other Aluminum alloys and it is weldable.

Prior to the cold plate design, the following aspects need to be addressed:

- The major heat sources of LRUs and the location
- Total heat load anticipated on the cold plate (on both sides for effective usage)
- The environment, the cold plate is going to operate?
- Mechanism of LRUs attachment to Cold plate
- Heat transmission path & and contact resistance associated with it
- What is the mechanism of cold plate attachment to the rack?
- Enhancement of heat transfer area
- Leak-proof sealing method of cold plate
- Liquid inlet and outlet design in order to attach with QDCs (Quick Disconnect Couplings)
- Interfacing connectors, fasteners

Vacuum brazing is selected as the cold plate fabrication process as the joint provides a permanent bond between the parts to be joined with the help of a brazing filler metal. The composition of the filler alloy is such that its melting point is slightly below the melting range of the parent metal of the parts. Hence the joints are strong and leakproof. Based on the total heat load of the LRUs and the heat source of specific LRUs, a conceptual model is made in CATIA. Since the heat sources of the LRUs are on one side, fins [3,4] to enhance the heat transfer are provided on that side. Initially, thermal analyses are carried out for a cold plate of size 1.8m x 0.24mx 0.012m in ANSYS fluent. The methodology adopted for cold plate development is shown in Figure 2.

III. CHALLENGES FACED

The first prototype cold plate is realized through vacuum brazing process as a single one of size 1.8m x 0.24mx 0.012m. Figure 3 shows the inner view of the two halves of cold plate across symmetry line on the left side each 6mm thick and 1.2m length. Fins are made by the machining process in the coolant flow [5] area to enhance heat transfer. Final cold plate after vacuum brazing [6,7] is shown on the right side in the same figure. Adapters to connect Quick Disconnect Couplings (QDCs) are welded to the cold plate after vacuum brazing. Inlet and outlet adaptors along with QDCs are encircled in the figure. However, after brazing in the furnace, it was observed that surface planarity was not maintained on the cold plate surface. The root cause for this is found as poor stiffness of the plate. As observed in the inner view of the cold plate in Figure 3, the material is scooped out to reduce the weight at the places where no heat sources are present, which is no flow area of coolant. Added to this, plate the thickness is much less compared to the length (100 times less than the length).

Due to the said reasons, it is decided to have two cold plates namely Single Row Cold Plate (SRCP), and Two Row Cold Plate (TRCP), instead of a 1.2 mm long plate. Grooves are made to enhance the stiffness at no flow area, rather than scooping the full material. Instead of having two equal 6mm thick half sections, two sections of 10mm and 2mm

thick are added together to a 12mm thick plate. Fins are made a little dense to increase stiffness at the flow area in the 10mm thick section. This is called a fin plate. The 2mm thick plate conceals the fin plate is called as cover plate. The two cold plates are thermally modeled, and thermal performance is analyzed and found satisfactory. Figure 4 shows the inner configuration of the fin plates. To address the planarity issue, it is decided to join the fin plate and cover the plate by vacuum brazing and machine to the desired thickness of 12mm(10 mm+2 mm). Inlet and outlet adapters as made as integral parts of a 10mm fin plate. The planarity issue is resolved due to these modifications. However, at a few locations minute gaps are observed at the joining line, and non-uniformity is observed in the thickness of the cover plate. These defects are shown in Figure 5. It is found that due to non-uniform heating during the vacuum brazing process, filler material did not flow uniformly resulting in minute gaps at the interfaces. By taking care of uniform heating and proper machining after brazing these issues are resolved.

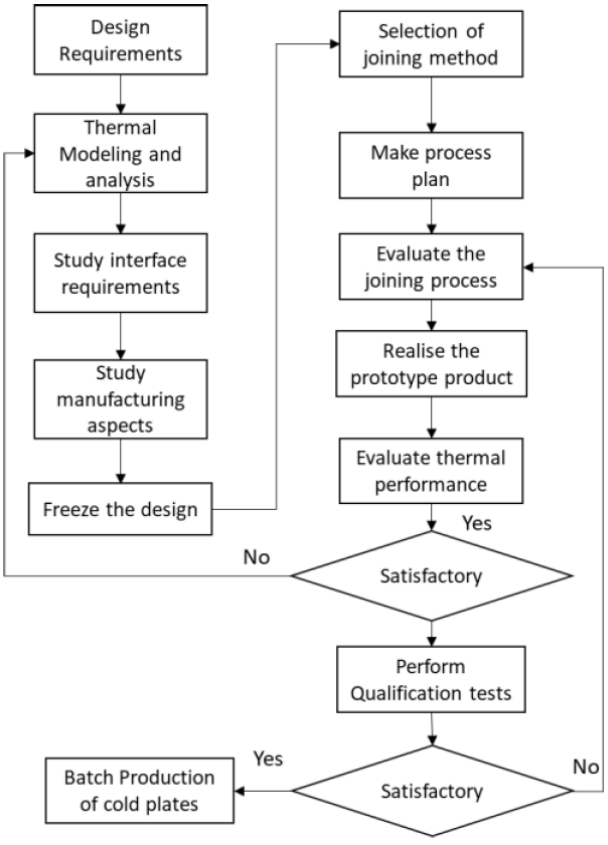

Figure-2 Cold plate development methodology

IV. THERMAL EVALUATION

The realized cold plate is thermally evaluated by attaching in a prototype rack and the coolant is made to flow through as per the heat load requirements. Thermocouples are placed at the identified points and temperature is measured. Observations made from the experiment are compared to the results obtained from the analyses. It is found that both are in close agreement to each other. The details of the analyzed model, experimental setup, and results comparison table are presented in Figure 6. Due to the additions of fins, the heat transfer area is increased approximately to 0.05m2 in the case of a single-row cold plate and 0.2m2 area is increased

Figure-3 Inner view of (left)Cold plate of 1.2m length vacuum brazed cold plate(right

Figure-4 Inner view of single row cold plate (left) two row cold plate (right)

Figure-5 Post defects: minute gap observed across the line of joint of fin plate and cover plate(left) non-uniform thickness of cover plate after (middle, right)

in the case of a two-row cold plate. This has enabled effective conduction heat transfer from the cold plate to the coolant.

V. QUALIFICATION TESTS

Cold plates inside the rack act as secondary support members and take the loads. The entire rack is proposed to be mounted inside the dome external to the aircraft. Hence the cold plates are subjected to the qualification tests as per the requirements provided in Table 1. Figure 7 provides the testing of cold plates at RCI facilities, in Hyderabad. Further burst pressure test is carried out to verify the strength of the brazing. Figure 8 shows the test setup made for burst pressure. It is observed that a small bulge at the brazing portion occurred at 30 bar pressure for a single-row cold plate and the crack opened at 58 bar pressure. For the two-row cold plate at 30 bar pressure bulging happened at the brazing portion and at 48 bar cracks opened. The maximum pumping pressure

Table-1

Sl. No.	Test	Test Conditions / Reference Standards	Remarks
1	Vibration	MIL-STD-810D	Visual Examination (VE) after the test
2	Fungus	Temperature: 30°C ±2°C RH: Not less than 95%, Duration: 28 days	This test may be carried out on representative samples. VE at the end of the test.
3	Salt Corrosion	MIL – STD – 810D, Method 509.2 Procedure – I	This test may be carried out on representative samples. VE at the end of the test.
4	Shock	As per MIL - STD - 810D, Method 516.3 – 8	VE after the test
5	Accelera-tion	Structural: MIL-STD-810D, Table 500.3	VE after the test
6	Transit Drop	No. of drops : 26 drops as per MIL-STD-810D,procedure IV,516.3(d)-II	VE after the test

of the entire coolant circuit is expected to be at 8 bar, the cold plates are found to be very safe for operating in the designed fluid circuit.

VI. ATTACHMENT ASPECTS

Since the cold plate has to be attached to the rack, collar-like projections is made at the corners and sufficient filleting is provided for strengthening

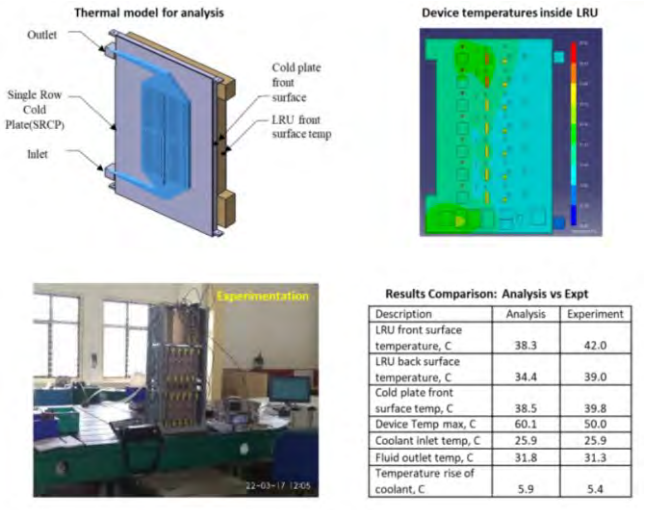

Figure-6 Thermal evaluation of cold plate: Analyses and experimentation, results comparison

Figure-7 Acceleration, Shock and vibration tests performed on cold plate

purpose. This is encircled in Figure 9. The collars of the cold plate have holes of 5mm so that they can be fastened to the rack frame structure using bolts. Also, to have good contact of LRUs with a cold

Figure-8 Burst test on cold plate

plate for effective heat transfer, wedge lock mechanisms are used on LRUs. LRU fitted with the wedge lock is shown in Figure 10

VII. CONCLUSIONS

Single and two-row cold plates are designed and developed using a vacuum brazing method that meets the cooling requirements. These are tested thermally and are also qualified as per FAR 25 regulations. In the process of development, the brazing process is established and the cold plate is proven to be airworthy

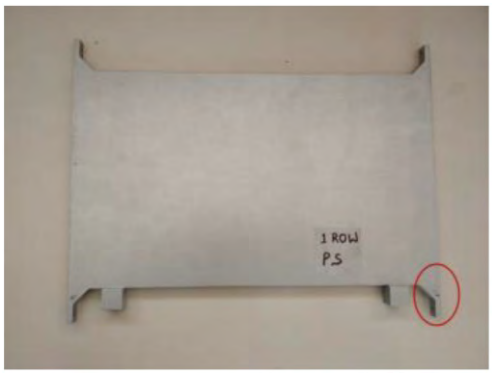

Figure-9 Cold plate with collar(encircled)

Figure-10 LRU with wedge lock mechanism

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Generative design for additive manufacturing of sounding rocket crown: A case study

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Abstract - Additive manufacturing has revolutionized the manufacturing sector with its unique capabilities such as high design freedom, reduced lead times and high efficiency. The advantages of additive manufacturing process such as lower lead time, increased efficiency and higher design freedom are highly synergic with requirements of aerospace sector, which include lower mass, manufacturing in less quantity, rapid prototyping, etc. Laser Powder Bed Fusion (LPBF) is a promising additive manufacturing technique that could demonstrate potential applications in aerospace sector.

To utilize the design freedom provided by additive manufacturing processes and to take advantage of aforementioned features, new design methodologies and practices must be adopted. Design for additive manufacturing (DfAM) involve a series of design approaches for optimum shape and weight selection for components without losing its functional characteristics. Numerical and computational tools such as shape optimization, topology optimization, generative design etc., are typical terminologies associated with DfAM (Kazi et al., 2017; Ponche et al.,2014). The aforementioned approaches coupled with smart practices such as artificial intelligence and machine learning algorithms to produce further improvisation in design.

This paper presents a case study of generative design for additive manufacturing (metal 3D printing) of a space component, 'the crown' of a Hybrid Propulsion Experimental Rocket - Demonstrator (HyPER-D). The study presented in this paper is an attempt to demonstrate the role of generative design and subsequent simulations for additive manufacturing, to improve the configuration of a functional component in terms of mass budget and mechanical characteristics. Design iterations/ optimization for the selected component for metal additive manufacturing using Laser Powder Bed Fusion (LPBF) technique, and its comparison with subtractive (machining) route has been presented as a case study. As an outcome of generative design, the crown component has been successfully re-designed for LPBF using AlSi10Mg powder, with improved factor of safety and reduced part deformation having a mass saving of around 50%, in comparison with conventional manufacturing using stainless steel.

Typical process flow and component designs are presented in Figure 1 and 2.

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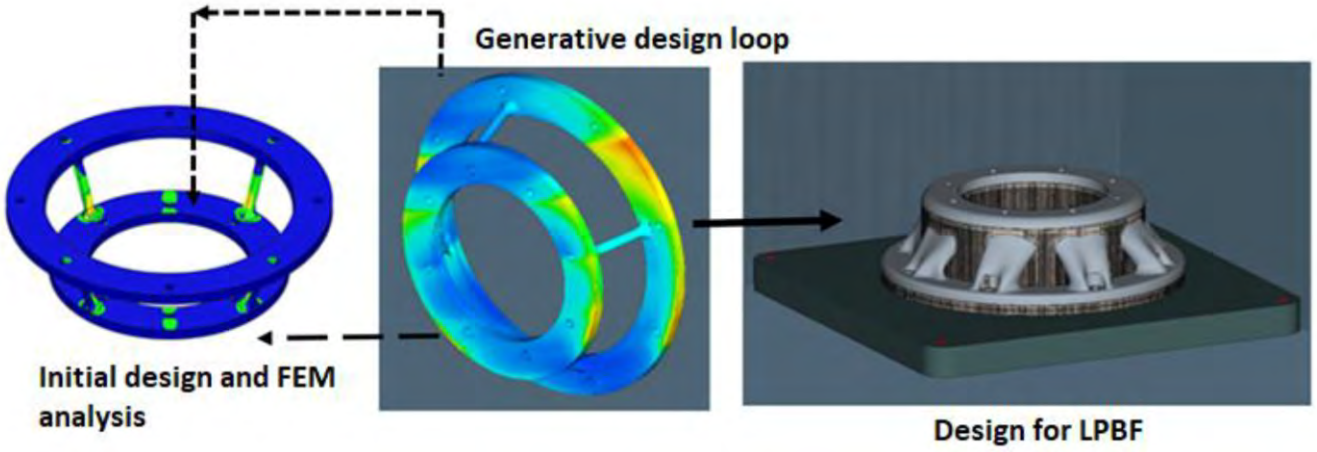

Fig.1 : Process flow of generative design approach for Crown Component

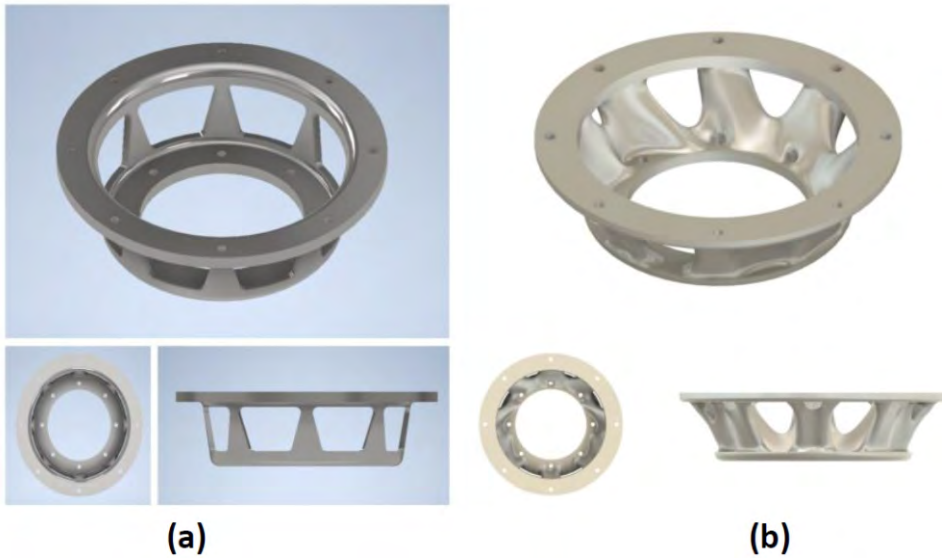

Fig. 2: Design made for (a) conventional manufacturing and (b) new design optimised for LPBF.

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Functional Hazard and Fault Tree Analysis for the Flight Control System of a Transport Aircraft

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Abstract - This paper outlines the approach to develop a Functional Hazard and Fault Tree analysis for the Flight Control System (FCS) for a commuter airplane. Functional Hazard Analysis (FHA) has been conducted for the FCS system to point out and categorize hazards that may jeopardize flight safety due to malfunction of FCS. In addition, Fault Tree Analyses (FTA) have been carried out for severe major and catastrophic hazards identified by FHA of the FCS. Through a comprehensive fault tree analysis, it has been demonstrated that the probability of catastrophic events occurring due to the malfunction of FCS is less than 1e-9 [1]. A comprehensive explanation of the techniques and approaches employed to fulfill safety requirements, as stipulated in the Federal Aviation Regulations (FAR) 23 Advisory Circular 1309-1E, has been provided. The necessity of redundancy to preclude single point failure through redesign of elevator circuit and to satisfy regulatory requirements has been shown through FHA and FTA.

Keywords - Flight Control System, Functional Hazard Analysis, Fault Tree Analysis.

I. INTRODUCTION

The Flight control system (FCS) consists of primary and secondary controls used for pitch, roll and yaw of the aircraft. The primary flight controls are ailerons, elevators and rudder. The secondary controls comprise of trim tabs elevator , aileron, and rudder in addition to flaps. Control column with wheel is provided in the cockpit for the operation of elevator and ailerons by the pilot. The same is replicated on the co-pilot side. These dual control columns are interconnected. Similarly, dual rudder pedals are provided in the cockpit for operation of rudder and are also interconnected. Displacement of the control column, wheel and pedals in the cockpit is transmitted to the respective control surface through a combination of cables, pulleys, torque tubes, levers and push pull rods. Cable control has been duplicated wherever it is used. The range of movement of control wheel and rudder pedals is limited by mechanical stops. Flaps are electrically operated through irreversible screw jacks. Trim tabs are operated by irreversible electrical actuators through respective switches provided in the cockpit.

The Functional Hazard Analysis (FHA) for the Flight Control System (FCS) primarily focuses on recognizing and categorizing functional hazards or failure scenarios that could impact the safe operation of the aircraft across its entire range of flight conditions and various phases of flight. FHA employs a top-down approach to functional analysis, aiming to identify failure scenarios, evaluate their consequences and classifications, and establish safety objectives for system design.
The present hazard analysis has been limited to identifying Catastrophic and severe major events associated with the flight control system that are crucial for aircraft functions.

Fault Tree Analysis has been performed for events which have been identified as catastrophic and severe major as required by FHA. These form part of safety requirements laid out in (FAR) 23 Advisory Circular 1309-1E. The Fault Tree itself is a grouped pictorial depiction of the failures or undesirable factors causing the occurrence of a defined unwanted circumstance, defined as the top event. The pictorial representation is in a form which can be comprehended, analysed and if found necessary, regrouped to help the identification.

Fault Tree Analysis is basically a deductive (top down) method of analysis aimed at pinpointing the causes or combinations of causes that can lead to the defined top event of loss of pitch, yaw or roll control functions [2]. The FTA results should demonstrate that the probability of failure for catastrophic and severe major events are less than 1E-9 and 1E-7 per flight hour respectively, but also ensure that there are no single point failures for these events. To ensure that the above criteria are met a number of design improvements have been undertaken for the FCS. A thorough design appreciation has been undertaken to ensure that safety provisions meet or exceed regulatory guidelines. Redundancy management has been given topmost priority to ensure that there are no single point failures for catastrophic events for FCS are avoided. These are discussed in the sections IV, V and VI

II. DESCRIPTION OF PRIMARY FLIGHT CONTROL SYSTEMS

1. Aileron Control System: Clockwise and anti-clockwise rotation of the control wheel fitted on the control column in the cockpit provides the aileron control. The control wheels on the dual control column are interconnected. Rotation of the control wheel is limited by mechanical stops, while aileron movement is limited by surface stops. The rotational movement of the control wheel is transmitted to the aileron through cable and push, pull rods. Table I shows the range of Control wheel and corresponding aileron movement.

TABLE I . CONTROL WHEEL AND AILERON MOVEMENT IN DEGREES

Control Wheel Rotation	Aileron Movement	
	Right	Left
40° ± 1° Left	18° ± 1° Up	13°± 1° Down
40° ± 1° Right	13 °± 1° Down	18°± 1° Up

2. Elevator Control System: Dual control column with wheel is provided in the cockpit for the operation of the elevator control. The control columns are interconnected through the torque tube on which they are mounted. The forward and aft movement of the control column is transmitted to the elevator through torque tube, bell cranks, levers, cables, tie rods and push pull rods. Forward and aft movement of the control column is limited by mechanical stops. Elevator movement is limited by the surface stops. A disconnect mechanism has been provided by means a clutch between the LH elevator and the RH elevator so that in case of Jamming of any elevator, the other elevator can be independently operated preventing catastrophic loss of pitch control. Table II shows the range of Control column and corresponding elevator movement.

TABLE II . CONTROL WHEEL AND AILERON MOVEMENT IN DEGREES

	Control Column Angle (Deg)	Elevator
Aft (w.r.t Neutral)	13 ±1/2°	22 ±1°Up
Neutral	11 +0.5°	0° (w.r.t Vertical)
Fwd (w.r.t Neutral)	12.5 ±1/2°	22 ±1° Down

3. Rudder Control System: Dual rudder pedals are provided in the cockpit for the operation of rudder control. The rudder pedal assembly consists of two vertical bars, each mounted on a horizontal arm and a pedestal. The rudder pedal movement is transmitted to the rudder through cables, tie rods, quadrants and push pull rods. Cable control is duplicated wherever it is used. The rudder pedal movement is limited by the mechanical stops provided in the system. The rudder movement is limited by the surface stops. Table III shows the range of rudder pedal and rudder movements

TABLE III . RUDDER FOOT PEDAL MOVEMENT IN MILLIMETRES AND CORRESPONDING RUDDER MOVEMENT IN DEGREES

Rudder pedal movement	: ± 110 mm
Rudder movement	: ± 24° ± 1°

III. DESCRIPTION OF SECONDARY FLIGHT CONTROL SYSTEMS

1) Flap System: The aircraft is fitted with single slotted fowler flaps, two on each wing. The flap system is operated by a Power Drive Unit (PDU), located in the centre section of the aircraft. The power drive unit is equipped with torque limiter, limiting the maximum torque on each side. The mechanical design prevents asymmetry between each output shaft. Both position signals coming from the position sensors are continuously compared in the control unit. If the difference is greater than the finite threshold (about 0.5° at 0° Flap position to 3° at 20° Flap position) the flap position lever and control unit stop the PDU. The flap position is indicated in the cockpit. The flap operation time from UP (0°) to landing position (20°) is about 20 seconds. The flap positions provided are as follows: 0° (UP), 10° (Takeoff) and 20°, 30° (Landing).

2) Aileron Trim Tab: The Aileron trim tab has been positioned at the inboard trailing edge of left aileron. because of commercial viability. Aileron trim tab is operated by an irreversible DC electrical actuator. This actuator is located in the nose box of the aileron and is connected to the operating horn of the aileron trim tab through a bell crank and a tube assembly. The electrical power is supplied to the actuator both from the normal and standby electrical power supply (28 VDC). Normal operation of the aileron trim tab is through the roll trim switch provided on the control wheel assembly in the cockpit. The standby trim switch is provided on the center pedestal in the cockpit. The range of operation of the aileron trim tab is ± 15 ±0.5°. The trim tab position is indicated on a triple trim position indicator located on the MIP in the cockpit.

3) Elevator Trim Tab: Trim is carried out by the pilot using the normal pitch trim switch located on the control wheel assembly or the standby pitch trim switch located on the pedestal in the cockpit. Manual trim usage will automatically isolate the auto pitch trim. In both the Auto and manual trim mode, the trim tab operation is carried out by a servomotor located in the horizontal stabilizer through a capstan, cable, irreversible mechanism, torque tube and tube assemblies. The trim tab movements are +8° (tab down) and 15° (tab up). The trim tab position is indicated on a triple trim position indicator located on the MIP in the cockpit. The electrical power is supplied to the servomotor both from the normal and emergency power supply (28V DC).

4) Rudder Trim Tab: Rudder trim tab is operated by means of an irreversible D.C electrical actuator. The actuator located in the nose box of the rudder is connected to the operating horn of the rudder trim tab through a bell crank and a tube assembly. The electrical power is supplied to the actuator both from normal and standby electrical power supply (28VDC). Both normal and standby operation of rudder trim tab is through the yaw trim switch . This switch is located on the center pedestal provided in the cockpit. The range of operation of the rudder trim tab is ±15°± 0.5°. The trim tab position is indicated on a triple trim position indicator located on the MIP provided in the cockpit.

IV. DESIGN IMPORVEMENTS

Following design changes have been made to improve the performance of the mechanical FCS:

1. In the aileron circuit, guide pulley has been replaced by a compound pulley, where the cable stretch, and slip is reduced.
2. Flanged Vari seals are introduced on two torque tubes in the aileron circuit to prevent pressure leak from cabin.
3. The Rudder pedal assembly design has been changed to improve torsional stiffness.
4. The Rudder Quadrant has been redesigned to decrease lever ratio to reduce cable load. Bell crank lever has been changed to Torque tube assembly, in commensurate with redesigned Quadrant.
5. Elevator Quadrant has been redesigned to decrease the lever ratio to reduce the cable load.
6. The balance tab on the left-hand side of the elevator has been converted with surface area increase as an additional trim tab
7. An elevator disconnect clutch has been

provided to disconnect the LH and RH elevator in case of Jamming

8. The cable system for the aileron, rudder and elevator circuit has been changed from nylon jacketed cable to steel cables to reduce friction.

IV. SAFETY PROVISIONS

The following safety measures have been implemented for the FCS

1. To ensure sufficient cable strength, only cables with a diameter greater than 1/8 inch have been utilized in primary flight control systems.
2. Every cable system has been meticulously designed to maintain consistent cable tension across the entire range of travel, regardless of the prevailing operating and thermal conditions.
3. Turn barrels have been provided for the cable assemblies to facilitate tensioning of the cables
4. Visual inspection provisions have been provided at every terminal, pulley, turnbuckle, and fairlead.
5. Each pulley is matched to the specific cable it is intended to be used with respect to its size and type. Standard pulleys and turn barrels are used for the cable control confirming to Army Navy/ Military standards.
6. Every pulley is equipped with snugly fitting protective covers to ensure that the cables remain in their proper positions and do not become entangled, even when they are slack. Each pulley is situated within the plane that the cable follows, preventing any contact between the cable and the pulley's edges.
7. Fairleads have been positioned in such a way that they cause no deviation in the cable's direction greater than 3 degrees.
8. Clevis pins that are subjected to loads or motion and secured solely by cotter pins are not permissible for use within the FCS.
9. Turnbuckles have been attached to components with angular motion in a manner that ensures there is no possibility of binding across the entire range of motion.
10. For every component with clearance (a loose fit) exposed to impact, jerk or vibration, there is a sufficient bearing factor in place to account for the typical relative motion effects.
11. Compliance with the factors prescribed in FAR Secs. 23.657 & 23.693 has been met for control surface and hinges.
12. For any fitting whose strength hasn't been confirmed through load tests that accurately simulate stress conditions within the fitting and its adjacent structures, a factor of no less than 1.25 has been applied to each component of the fitting and its attachment methods. The structural elements have been designed to the best extent possible to minimize areas of stress concentration, especially in locations where cyclic stresses exceeding the fatigue limit are expected during regular operational conditions.
13. Control surface limit load tests have been conducted, encompassing the examination of the fitting to which the FCS is connected.
14. Movable surfaces have been installed in a way that ensures there is no contact or intrusion between any of the surfaces, their supporting structures, or neighboring non-movable structures. This is relevant when one surface is maintained at its most crucial clearance position, while the others move throughout their entire range.
15. Control surface hinges, excluding ball and roller bearing hinges, have been designed to have a safety factor of at least 6.67 with respect to ultimate bearing strength of the softest material utilized as a bearing.
16. For roller or ball bearing hinges, the permissible bearing rating has not been surpassed.
17. All the rotating parts have been mounted on the bearings to ensure smooth operation.
18. The torque tube is mounted at the ends on single row rigid ball bearing.
19. Pulleys and quadrants are provided with rigid ball bearing at the fulcrum.
20. The levers are provided with rigid ball bearing at the fulcrum and self-aligning ball bearing at the tube assembly attachment point.

21. Retention of bearing in the housing is by staking as per standard staking practice.

VI. REDUNDANCY MANAGEMENT

Redundancy Provisions for Flight Control System: The cables used for transmission of forces for the primary pitch, roll and yaw control have been duplicated. In the event of failure of one cable, the other cable is available as hot redundant. If the structural links, levers etc. get jammed or inoperative in case of the LH / RH elevator, a disconnect mechanism has been provided between the LH & RH elevator in addition to the respective trim tab, adequate for carrying out safe landing of the aircraft. . Trim Tab actuators for all the three systems have been provided with electric power from normal and stand-by supplies. Redundancy is available in the form of two trim tabs (L.H & R.H) for the elevator. In case of yaw control, differential thrust of engines could be used for safe landing of the aircraft as an additional redundancy. Redundancy is available for manual trim operations of aileron and elevator control systems as normal and stand by switches are available.

VII. FUNCTIONAL HAZARD ANALYSIS

The Aircraft FHA format is presented in a tabular format that encompasses the following elements.

1. **Item No:** This number indicates the serial number of the considered functional hazard for the given system.
2. **Functional Hazard:** The failure condition (top event) identified here without reference to any cause.
3. **Flight Phase:** All phases of flight are identified which are significant for hazard under consideration namely Taxiing, Take-off and climb, Cruise, Approach, Landing/Touch down and Parked.
4. **Effect on Aircraft:** This defines the effect of the mal-function on the aircraft during each specific phase of flight.
5. **Crew recognition/Crew action/Work load on crew:** Identifies whether or not the failure condition is annunciate, how it is recognized by crew and what course of action (if any) is available to the crew to counter or reduce the effect of mal-function.
6. **Criticality:** The criticality of failure condition is defined in accordance with the criterion set-forth in FAR23 Advisory Circular 23.1309-E [3] and SAE ARP-4761 [4] for system safety & Assessment is as reproduced below in Table IV.
7. **Requirement:** This defines the applicable certification authority requirement, special conditions etc.
8. **Acceptable Probability:** This defines the probability which must be met for the failure conditions (Top event).

TABLE IV [3]. SEVERITY GRADING AND ACCEPTABLE PROBABILITY OF FAILURE

Sl. No.	Category	Explanation	Acceptable Probability
1.	No Safety effect	Failure conditions doesn't cause any effect on the system, crew or occupants	—
2.	Minor	Failure conditions include a slight reduction in the safety margins or functional capabilities, a slight increase in crew workload such as routine flight plan changes or some in convenience to the occupants.	<1E-03/ flight hour
3.	Major	Failure conditions include a significant reduction in the safety margins or functional capabilities, a significant increase in crew work load or in conditions	<1E-05/ flight hour

Sl. No.	Category	Explanation	Acceptable Probability
		impairing crew efficiency or some discomfort to the occupants.	
4.	Severe major (Hazardous)	Failure conditions include a large reduction in safety margins or functional capabilities, higher work load or physical distress such that the crew could not be relied on to perform its tasks accurately or completely or adverse effects on occupants	<1E-07/ flight hour
5.	Catastrophic	Failure conditions which could prevent safe flight and landing	<1E-09/ flight hour

The total number of Hazards for each of the major aircraft system is listed in Table V.

TABLE V. NUMBER WISE BREAKDOWN OF HAZARDS FOR THE FCS OF AIRCRAFT

Number of Catastrophic Events	Number of Severe Major Events	Number of Major Events	Number of Minor Events
2	1	8	7

Subsequently, a list of the most important Catastrophic and severe major hazards has been prepared and listed in table VI. For each of the identified catastrophic / severe major hazard, design has been made to ensure that there is no single point failure. It will be shown from FTA that the computed probability of failure is less than the acceptable probability of failure for these catastrophic/severe major events.

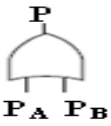
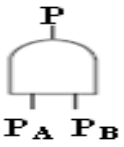
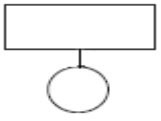
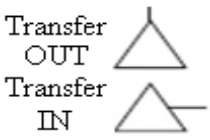
TABLE VI. : LIST OF CATASTROPHIC / SEVERE MAJOR HAZARDS

Sl. No.	System	Identified Catastrophic / Severe Major Hazards
1.	Primary Flight Control System	1. Loss of roll control 2. Loss of yaw control 3. Loss of pitch control

VIII. FAULT TREE ANALYSIS

Fault tree analysis has been performed for the most important Catastrophic/ Severe major events identified in the FHA. It has been assumed that the installation of equipment is free from errors and routine maintenance has been carried out at appropriate intervals. Generally, the failure data obtained from field failure rate is the most dependable. Often this situation may not be available, and the next best is the vendor predicted data from the state of design and technology used. In the absence of the above, MTBF/ failure data are used from NPRD database. The Fault Tree symbols and descriptions are shown in Table VII.

TABLE VI. : LIST OF CATASTROPHIC / SEVERE MAJOR HAZARDS

State	Symbol	Description
Logic Gates		**OR Gate** indicates that output event occurs if any of input events occurs. $P = P_A + P_B - P_A.P_B$
		**AND Gate** indicates that output event occurs only if all the input events occur at the same time. $P = P_A.P_B$
Input Events		Basic event represents a basic equipment failure that requires no development of failure causes
Transfer Symbol		Transfer-OUT symbol indicates that the fault tree is developed further at the occurrence of corresponding Transfer-IN symbol

The probability of failure for catastrophic/ severe major events along with the description of events obtained from the FTA is shown in Table VIII. The order of cut set has also been shown in the same table.

TABLE VIII : FAILURE PROBABILITIES OF IDENTIFIED EVENTS

Sl. No.	Undesired Events	Severity category	Failure probability	Order of Cut-Sets
1	Loss of Roll Control	Catastrophic	2.55E-11	2nd order
2	Loss of Pitch Control	Catastrophic	8.12E-11	2nd order
3	Loss of Yaw Control	Hazardous	7.29E-11	2nd order

IX. RESULTS AND DISCUSSION

FHA and FTA have been carried out for the FCS of the transport aircraft. The probability of loss of pitch, yaw and roll controls are well within the the ARP 4761 criterion of 1E-9 per flight hour. The addition of the elevator disconnect clutch prevents single point failure of the elevator due to jamming. Table IX shows the FHA for the identified catastrophic and severe major events for FCS. Fig 1. and Fig 2. show the Fault Trees for Loss of Roll Control and Loss of Pitch Control respectively.

X. CONCLUSION

The identification of critical events leading to the loss of FCS through a methodical functional hazard analysis has been explained. The failure probabilities estimated through FTA for the event has been found to be meeting the specified requirement of ARP-4761 and FAR 23 AC 1309E. Further, from the appraisal of safety and redundancy provisions, it has been shown through these analyses; the design of aircraft adequately meets all the basic and mandatory requirements.

ACKNOWLEDGMENT

The authors wish to thank Director, CSIR NAL for his support in publishing this paper.

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[2] Lindy Ellis, Part 7: Guide to fault tree analysis, Reliability of systems, equipment and components, British Standard BS 5760-7:1991IEC 1025:1990

[3] Advisory Circular AC 23.1309-1E. Systems safety analysis and assessment for Part 23 Airplanes

[4] ARP 4761. 1996. Guidelines and Methods for conducting the Safety assessment process on civil airborne systems and equipment

TABLE.IX FHA FOR LOSS OF PRIMARY FCS FUNCTIONS

Item No.	Functional Failure	Flight Phase	Effect on Aircraft	a) Crew Recognition b) Crew Action c) Workload on Crew	Criticality	Requirement	Required Probability	Remarks
1	Loss of primary Roll control	All	Almost total loss of roll control since both sides of linkages are interconnected. Trim tab control can provide only 2% of extent of clearing the roll moment available from fullaileron deflection	a. Self-evident b. Apply pressure to the extent of clearing the jam. c. High Work load	Catastrophic	AC 23.1309-1E FAR 23.671	IE-07	Method of compliance: (i) Safety Assessment: Will be proven by FTA that the failure mode is extremely improbable.
2	Loss of primary Pitch control	All	As both sides of linkages are connected by means of a clutch,	a. Self evident b. Explore possibility for clearing the jam.	Catastrophic	AC 23.1309-1E FAR 23.685 FAR 23.671	IE-09	Method of compliance: (I) Safety Assessment:

Item No.	Functional Failure	Flight Phase	Effect on Aircraft	a) Crew Recognition b) Crew Action c) Workload on Crew	Criticality	Requirement	Required Probability	Remarks
			pitch control is still possible. Only a jam involving the clutch, both LH and RH elevators are unserviceable resulting in the loss of Pitch control.	Use trim tab to extent available. c. High Work Load				Will be proven by FTA that the failure mode is extremely improbable.
3	Loss of primary Yaw control	All	Total loss of Directional control	a. Self evident b. Execute directional control through thrust modulation. c. High work load	Severe Major	AC 23.1309-1E FAR 23.1309 FAR 23.685 FAR 23.671	IE-09	Method of compliance: (i) Safety Assessment: Will be proven by FTA that the failure mode is extremely improbable.

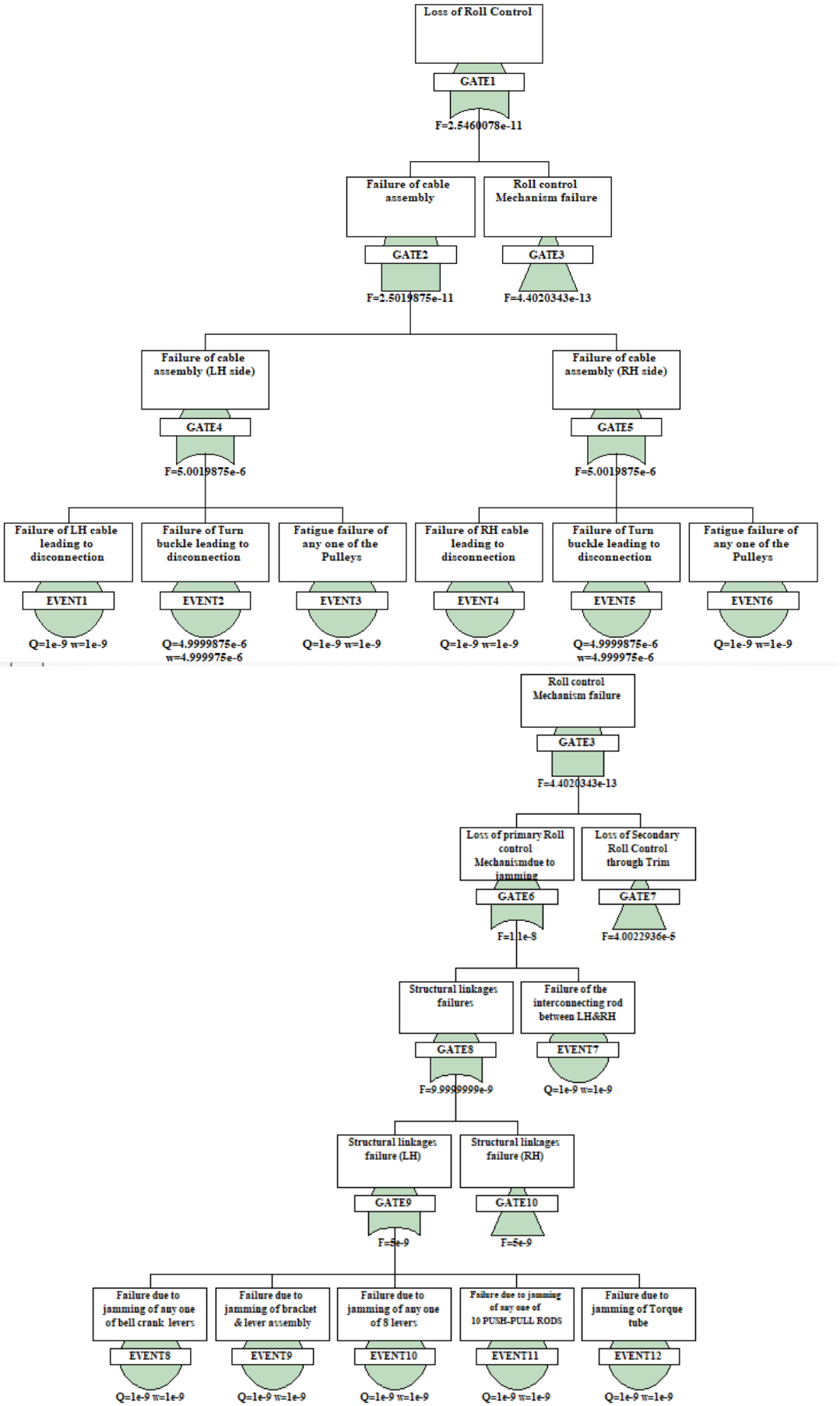

FIG 1. FAULT TREE ANALYSIS FOR LOSS OF ROLL CONTROL SYSTEM

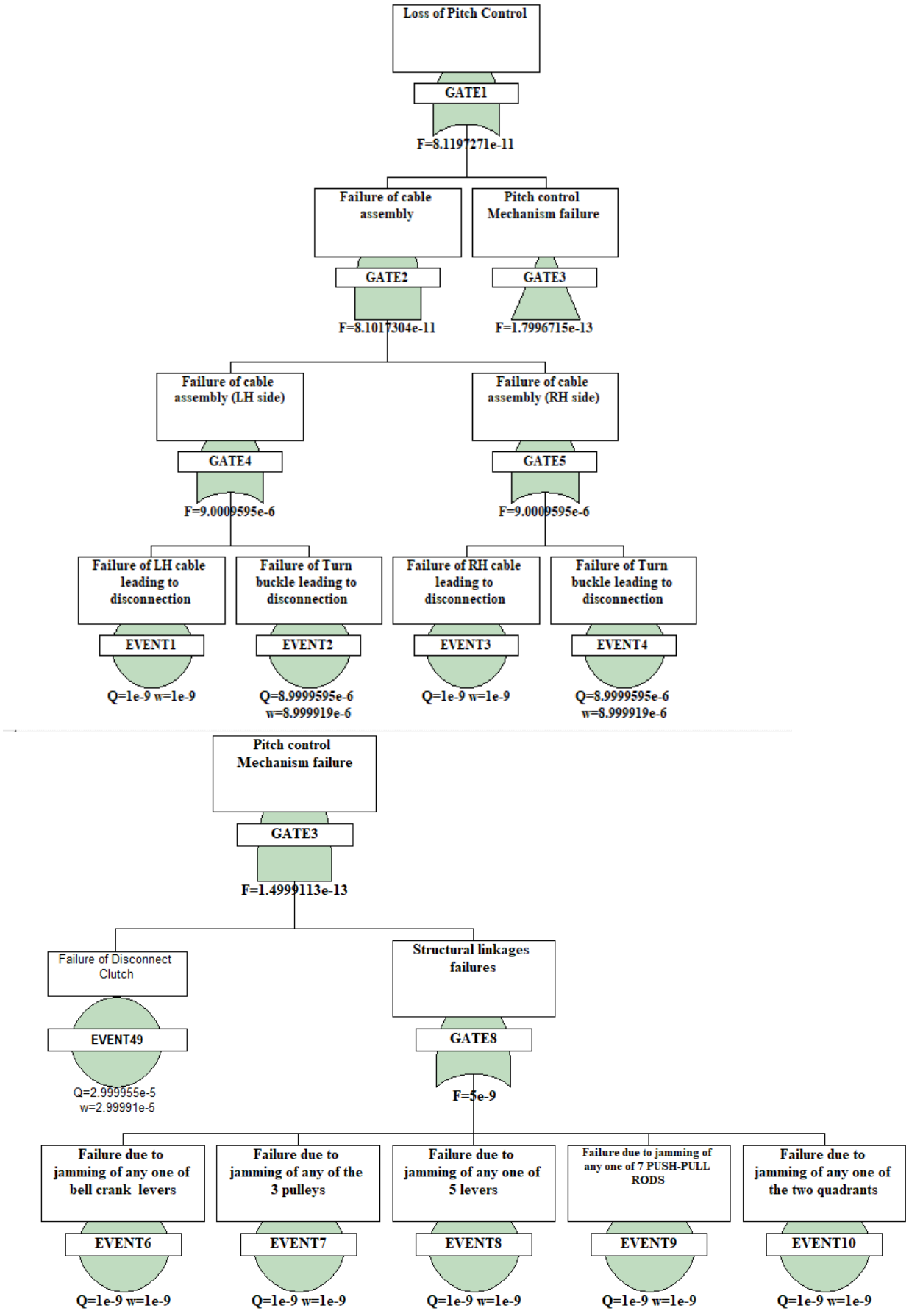

FIG 2. FAULT TREE ANALYSIS FOR LOSS OF PITCH CONTROL SYSTEM

Development of Novel Techniques for Sensing the Propellant Depletion of Low Thrust Engines

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Abstract - In small satellite launch vehicles, multiple low-thrust engines are used for orbit raising, de-boosting, vehicle attitude control, and maneuvering before or after satellite injection. These engines may have to burn for longer durations based on the performance of lower stages for correcting the orbit. During the orbit correction, propellant depletion can happen before satellite separation, resulting in the loss of the launch vehicle's attitude control and maneuvering capability. Hence, propellant depletion detection with sufficient fuel margin is necessary, and the cutoff of the engines is issued at the required leftover propellant to use for attitude control and maneuvering purposes. This paper proposes novel techniques for sensing the depletion with sufficient fuel margin and comparing their performances. Based on the performance for normal and failure mode scenarios, the Adaptive Velocity threshold depletion Detection Logic (ADVDL) is recommended for implementation in the On-Board computer of small satellite launch vehicles.

Keywords - adaptive threshold, depletion sensing, multiple burns, orbit correction

I. INTRODUCTION

Small satellite launch vehicles comprise a liquid stage as a terminal state consisting of multiple low-thrust engines. This terminal stage is used for correcting orbit deviations due to the off-nominal performance of lower (typically solid) stages, attitude control of the vehicle, and maneuvering before or after satellite injection for collision avoidance. The burn duration of the stage depends upon the loss or gain of velocity at the end of the previous phase. As the thrust provided by the engine is low, the burn duration is higher for generating the required velocity to correct the orbit. If the fuel is depleted during orbit correction, attitude control, and maneuvering capabilities are not attained. This results in higher body rates, attitude errors at satellite injection, and a higher probability of satellite collision with the stage. Hence, a scheme for detecting the propellant depletion with sufficient fuel margin is required in the On-Board in the absence of reliable propellant level sensors. The cutoff command can be issued at the required leftover propellant for attitude control and maneuvering purposes. This paper focuses on novel techniques for detecting propellant depletion with fuel margin and recommendations based on their performances for nominal and off-nominal conditions.

II. ISSUES WITH ACCELERATION BASED SENSING SCHEMES

In heavy satellite launch vehicles, the thrust delivered by the liquid stage is usually very high. Due to the higher acceleration levels and significant change in acceleration near depletion, propellant depletion is sensed through acceleration. The command for engine cutoff is

issued if the acceleration is lower than the threshold acceleration value, and vehicle attitude control is attained through dedicated control thrusters after engine cutoff. The difficulties associated with propellant depletion detection using threshold acceleration-based techniques for small satellite launch vehicles are

- Thrust and mass flow rates change as the propellant is consumed due to the blow-down characteristics. Thereby, the rate of change of acceleration near depletion is lower, as shown in Fig. 1. A trivial change in acceleration results in a significant change in propellant consumption, which demands highly accurate and high-resolution accelerometers.
- Due to the wide range of engine performances in terms of thrust and specific impulse, acceleration at the time of depletion varies broadly, as shown in Fig. 1. Hence, accurate detection of depletion is difficult using single threshold acceleration.
- Orbit correction is through thrust generated by the engines, and attitude control is attained by switching off (off modulation) a specific number of engines. Due to the engine off operation for attitude control, acceleration reduces significantly (20%), as a spike is shown in Fig.2. In these scenarios, the threshold acceleration-based scheme triggers false detection with significant leftover propellant.
- As the acceleration level is low, noise effects may dominate and cause inaccuracy in detecting depletion with propellant margin.
- Engines are used for multiple satellite separations in different orbits using multiple burns. As the burn duration of each phase varies based on the performance, pre-selection of the acceleration threshold for each burn is difficult.
- Engine failure in off conditions reduces the acceleration and propellant consumption. In such scenarios, the threshold acceleration-based sensing scheme triggers false detection with a significant leftover propellant.

Due to the above reasons, threshold acceleration-based propellant depletion sensing with fuel margin cannot be implemented for small satellite launch vehicles. Hence, novel techniques for low-thrust engines are proposed to detect propellant depletion with fuel margin

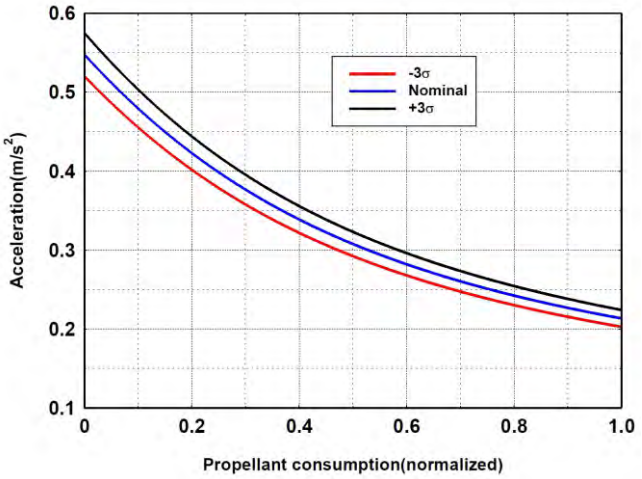

Fig. 1. Acceleration for nominal and off-nominal performances

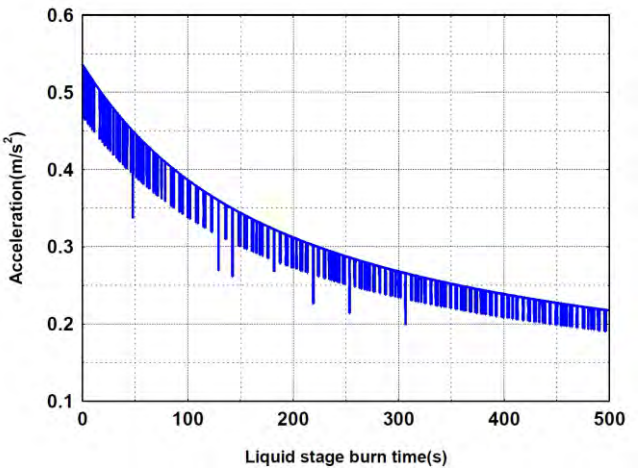

Fig. 2. Acceleration with off-modulation operation of engines

III. PROPOSED METHODS

Unlike high thrust liquid engines, problems are associated with acceleration-based sensing of propellant depletion in low thrust liquid engines. The following techniques are proposed to accurately detect depletion with fuel margin to overcome the acceleration-based sensing scheme difficulties.

- Propellant Mass based depletion Detection Logic (PMDL)
- Augmented Acceleration depletion Detection Logic (AADL)

- Adaptive ΔV threshold depletion Detection Logic (ADVDL)

A. Propellant Mass based depletion Detection Logic

Propellant mass consumption is computed in the On- Board using the engine on/off commands generated by Digital Autopilot and propellant flow rate characteristics shown in Fig. 3, derived by assuming the nominal thrust and specific impulse. The propellant flow rate versus propellant consumption is represented using a fifth-order polynomial. Propellant consumption in a time cycle due to engine-on commands is computed using (1).

$$m_r = \sum_{i=1}^{n} R_i \times \dot{m} \times \Delta t \quad (1)$$

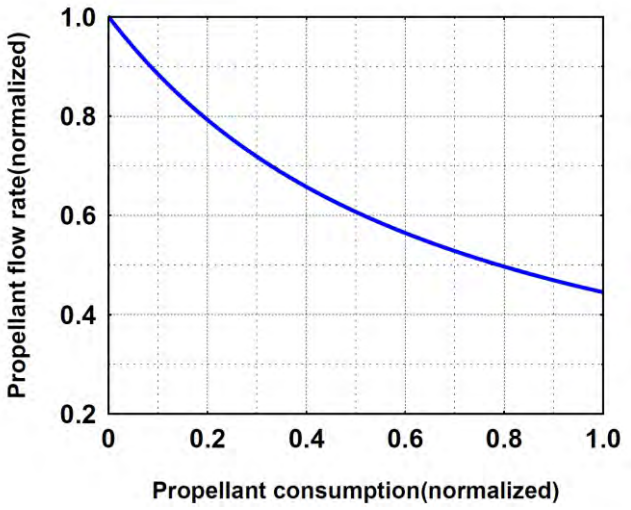

Fig. 3. Propellant flow rate characteristics of a single engine

Where n is the total number of engines in a stage, R_i is the on/off command for i^{th} engine, $\dot{m}$ is the propellant flow rate for each engine, Δt is time interval, and m_r is propellant consumption per cycle.

As the liquid stage propellant is used for attitude control in coast phases during the lower stages, integration of propellant consumption per cycle from vehicle liftoff gives the total consumption. Cutoff of the engines is issued if the total propellant consumption reaches the allowable propellant consumption. The major drawback of the scheme is that there is no feedback, i.e., the actual engine status is not considered for computing the propellant consumption. If the engine fails in on or off condition, actual consumption is higher or lower than the calculated consumption. Hence, this scheme cannot handle the failure mode scenarios of engines.

B. Augmented Acceleration depletion Detection Logic

The acceleration-based scheme uses the acceleration from inertial navigation sensors. One of the major drawbacks of an acceleration-based method is the reduction in acceleration due to the off operation of a specified number of engines for attitude control (off modulation), which reduces the acceleration and triggers the false detection of depletion. This issue can be avoided by augmenting the sensed acceleration with acceleration loss due to engines in the off condition to generate the total acceleration.

$$a_T = a_s + a_{off} \quad (2)$$

Where a_T is total acceleration, as is sensed acceleration, and a_{off} is acceleration loss due to engines in off condition.

Acceleration contribution by a single engine is computed using the sensed acceleration and number of engines in on status from the Digital Autopilot command.

$$a_e = \frac{a_s}{N_{in} \times \cos(\theta) + (N_{on} - N_{in})} \quad (3)$$

Where a_e is the acceleration due to single-engine firing, N_{in} is the number of engines connected to the stage in inclined position, θ is the inclination angle with respect to the stage axis, N_{on} is the number of on-status engines, and N_{off} is the number of off-status engines.

Acceleration loss due to engine off operation is equivalent to the acceleration contributed by a single engine multiplied by the number of engines in off condition.

$$a_{off} = a_e \times N_{off} \quad (4)$$

The cutoff command of the engines is issued if the total acceleration reaches the precomputed threshold acceleration value. This scheme requires the pre-computation of the acceleration threshold and the selection of the threshold for each burn. The threshold generation is hefty, especially during multiple burns, and requires high-resolution accelerometers to detect depletion with fuel margin accurately. As this scheme uses acceleration, detecting the propellant depletion during coast phases between the burns is not possible.

C. Adaptive ΔV threshold depletion Detection Logic

The ideal velocity generated by the stage upon consuming the propellant is described by the Tsiolkowski equation [1].

$$\Delta V = g I_{sp} \ln\left(\frac{m_0}{m_f}\right) \quad (5)$$

Where ΔV is the velocity generated by the stage, g is the acceleration due to gravity, I_{sp} is the specific impulse, m_0 is the initial mass of the stage, and m_f is the final stage mass.

In this scheme, the maximum ΔV(threshold ΔV) delivered by the stage in each burn is computed using the allowable propellant consumption and specific impulse. Cutoff command of the engines is issued if the accumulated sensed ΔV from the inertial navigation exceeds the threshold ΔV.

The remaining propellant at the start of each burn is unknown and depends on the propellant used for coast phase attitude control and burn duration of previous phases. The propellant consumed is computed with the flow rate characteristics and Digital autopilot commands using (1). As the ΔV delivered by the stage changes with satellite ejection, the ejected mass of the satellite is accounted for in computing the threshold ΔV. Equation (5) is modified to compute the threshold ΔV.

$$\Delta V_T = \Delta V_p + g I_{sp}\, f\, \ln\frac{\left(m_0 - m_c - \sum_{j=1}^{N} m_{sj}\right)}{\left(m_0 - \sum_{j=1}^{N} m_{sj} - m_c\right)} \quad (6)$$

Where N is the number of satellites, ΔV_p is the total velocity delivered till the previous phase, f is the reduction factor due to inclined engines (if any), m_c is the propellant mass consumed till the previous phase, m_{sj} is the mass of the satellite, m_t is the allowable propellant consumption, and ΔV_T is the threshold ΔV.

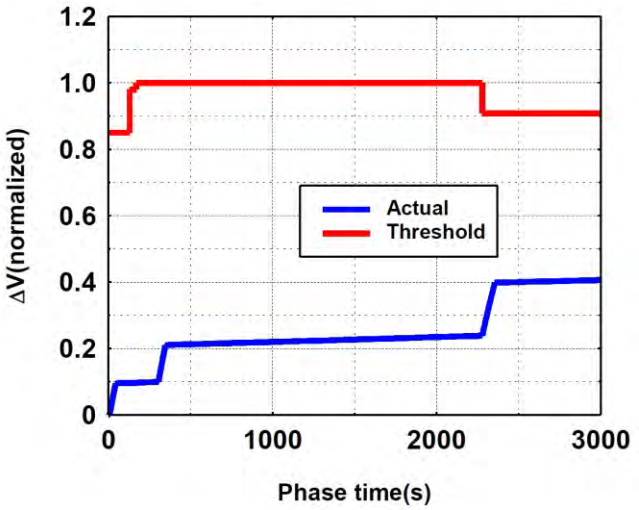

Fig. 4. Threshold and actual ΔV for multiple burns

Using (6), threshold ΔV is computed at the start of each burn and every satellite ejection by assuming a constant specific impulse. As the threshold is adjusted online using the burn duration and ejected satellite masses, as shown in Fig. 4, this scheme is mission-independent. It can be used for multiple burns without pre-computations. Since sensed ΔV from inertial navigation is used as feedback, reflecting the engine's on/off status, this scheme can handle the engines' off-nominal performance and failure modes.

IV. RESULTS AND DISCUSSION

Performances of schemes are validated through exhaustive simulations for nominal and off-nominal cases by perturbing sensitive parameters thrust, specific impulse, and mass of the stage and satellites up to ±3σ. The difference between the actual and allowable propellant consumption (error) at the time of engine cutoff is shown in Fig. 5. Propellant Mass-based depletion Detection

Logic reveals an error of 0.05kg for nominal and 2.35kg for off-nominal conditions. Higher error in off-nominal cases is due to the assumption of nominal propellant flow rate characteristics. Augmented Acceleration depletion Detection Logic and Adaptive ΔV depletion Detection Logic performances are comparable. Both the schemes show an error of 0.15kg for nominal and 1.2 to 1.3kg under off-nominal conditions. Following are the advantages of ADVDL over AADL

- Threshold ΔV is adjusted based on burn duration and ejected masses; hence, it is mission-independent. It does not require pre-computations of threshold values, whereas, in AADL, threshold accelerations are to be computed accurately for each mission.
- Cutoff of the engine can be issued during coast phases where the acceleration is very low.
- In AADL, thresholds are precomputed for normal conditions; hence, the failure mode of engines cannot be handled, whereas, in ADVDL, engine failure scenarios are handled.
-

The performance of Adaptive ΔV depletion Detection Logic under the failure of one of the engines in the off condition is shown in Fig. 6. The failure of the engine is simulated at 160s, which reflects the rate of change of actual ΔV. The difference between the actual and allowable consumption at engine cutoff is 0.4kg.

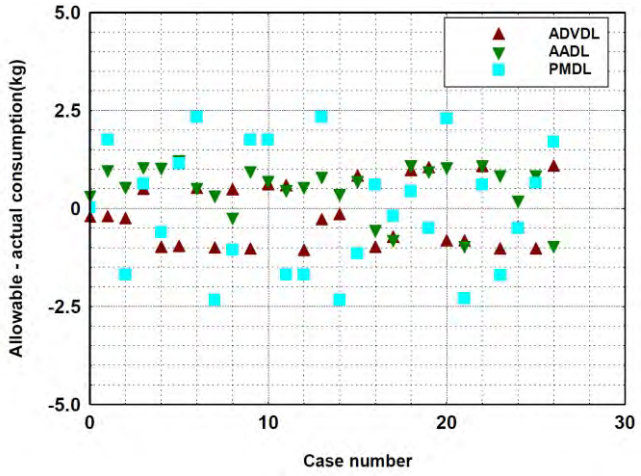

Fig.5. Difference between the allowable and actual consumption

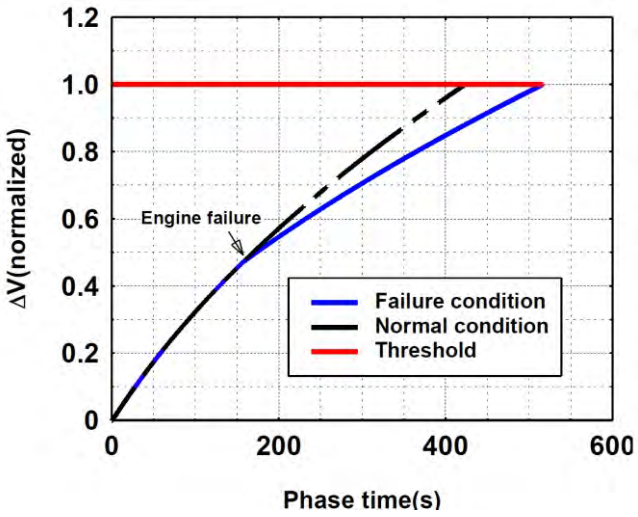

Fig. 6. Performance of ADVDL with engine failure

Adaptive ΔV depletion Detection Logic (ADVDL) is recommended for sensing propellant depletion with fuel margin based on the above advantages and performance.

V. CONCLUSION

To ensure that sufficient fuel is available for attitude control and vehicle maneuvering for multiple satellite separations, sensing the propellant depletion with adequate fuel margin is essential. Due to low thrust, there are difficulties with acceleration-based sensing schemes. Hence, novel techniques are formulated, and their performances are critically analyzed for normal, off-nominal conditions. Adaptive ΔV depletion Detection Logic (ADVDL) is recommended for implementation based on the following advantages.

- Pre-computation of thresholds for detecting the depletion with fuel margin for each mission is not required.
- As it uses ΔV feedback and computed propellant mass consumption, it can cater to additive ±3σ dispersions in thrust, specific impulse, and mass.
- Failure of engines in on/off conditions can be handled.

ACKNOWLEDGMENT

We thank Shri. E S Padmakumar, Director IISU/ISRO, for continuous support and meticulous reviews. His insights and expertise were instrumental in shaping the direction of this work.

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Implementation of Quality Management System through PLM framework

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Abstract - The objective of this study is to analyze the efficacy of PLM as an enabler for an effective quality management system - ISO 9001:2015 throughout the product lifecycle. The study first explores the fundamental concepts of PLM and its role in streamlining product development processes. In addition, the research focuses on the essential components of a quality management system and their alignment with the processes covered in PLM.

Through a combination of qualitative and quantitative research methods, data are collected from an R&D case study where the R&D deals with complex weapon platforms having integrated PLM with their existing quality management practices.

The study reveals that the QMS system implemented through the PLM framework has significantly improved adherence to QMS standards, and the efficiency of the processes in the design and development area in meeting the organizational quality objectives. Additionally, the implementation also benefited considerable reduction in audit duration and improved the accuracy of QMS audit.

Keywords - ISO Audit, PLM, Process Mapping, QMS, X-Matrix

I. INTRODUCTION

PLM systems and QMS systems coexist in many organizations. Since these systems, impact the core functioning of the organization they may be implemented in different time periods. Organizations want to take benefit of both systems. In addition, the expertise required to implement these systems are different. Therefore, different teams may implement the system.

Elements in PLM systems are highly information technology-oriented. On the other side, QMS components are process-oriented. In the situation of coexistence of PLM and QMS in an organization, We must understand if they are contradict or complementary to each other.

If they contradict each other, then it is better to understand the areas in which they differ. If they are complementary to each other, then we must know the areas in which they are supporting each other. While doing so, it is also prudent to verify, that PLM and QMS are really aligned with the

organizational objective. If so, from the components of PLM and QMS, are we able to connect the objective of the organization?

Answering the above question requires a study of an environment in which both PLM and QMS are implemented. Also, we need to have suitable management tools to visualize the correlations.

II. ANALYSIS OF A QMS SYSTEM IN PLM FRAMEWORK

A. Requirements of QMS: ISO 9001:2015

The QMS standard ISO 9001:2015 provides requirements for a quality management system to be implemented by an organization that is keen to demonstrate its capability in meeting customer demand and also to assure conformity to customer requirements.

While the requirements are grouped under various clauses of the standard, they focus on orienting all the key processes toward the organization's strategic objectives. Also, it emphasizes that organizations to pay attention to the uncertainties in their plans and their action to minimize the slippages.

ISO 9001:2015 lays down the requirements for QMS to an organization, striving for growth. The requirements give framework elements of processes in place to meet the quality objectives. Specifically, clause 4 of the standard demands that the organization must derive its objective from SWOT analysis. [1]

Clauses 3 to 4 cover the prerequisite (planning) for the operations to deliver a product or service which is covered in clause 8. Following Table 1 shows the clauses specifically applied to Design, Development, and production.

Table 1. ISO 9001:2015clauses specifically applied to Design, Development, and production

Sl. No.	Clauses	Clause No.
1.	Operational planning and control	8.1
2.	Requirements for products and service	8.2
3.	Design and development planning	8.3.2
4.	Design and development inputs	8.3.3
5.	Design and development controls	8.3.4
6.	Design and Development Outputs	8.3.5
7.	Design and development changes	8.3.6
8.	Control of production and service provision	8.5.1
9.	Identification and traceability	8.5.2
10.	Post-delivery activities	8.3.3
11.	Control of changes	8.5.5
12.	Release of products and services	8.6
13.	Control of production and service provision	8.7

B. Processes covered in PLM

PLM provides an IT solution for capturing and managing product information, right from the requirements phase to the 'obsolete' phase. This study focuses on the design and development phase.

The information generated at various stages of product development is captured as it flows through various workflows. Built-in configuration management modules in PLM manage version control and change management of complex systems. Modern PLM also has a project management facility, which extends the scope of PLM beyond the Product Data Management (PDM) functionality.

PLM supplied by OEMs is always configured/customized to the requirements of the organization implementing PLM. Alignment of the PLM processes with the objectives of the organizations must be followed to reap the benefit from the strategic implementation.

Following Table 2 shows, the key processes and features of PLM covered in the case study.

Table 2

Sl. No.	Processes and features of PLM
1.	Version control / Unique Numbering
2.	User Trial Approval Process
3.	Transfer of Technology Process
4.	Simulation Process
5.	Service Information Management
6.	Service Information Management
7.	Preliminary Design Review Process
8.	Online technical publication
9.	Online project management/Project Dashboard
10.	Design Release Process
11.	Engineering Change Management
12.	Document Creation / Approval Process
13.	Critical Design Review Process
14.	Configuration and Instance Management
15.	Concept Design Approval Process
16.	Access control
17.	Version control / Unique Numbering

C. Stages in the new product development

The study confines the following key processes (Table 3) in new product development.

Table 3

Sl. No.	Processes in new product development
1.	Product Development Plan
2.	Customer Requirements
3.	Designer's Specification
4.	Preliminary Design
5.	Preliminary Design Review
6.	Detailed Design
7.	Critical Design Review
8.	Prototype
9.	Test / Evaluation
10.	Transfer of Technology (TOT) / Production support
11.	Sustenance (Post-production support)

D. Metrix for PLM

Table 4 shows the typical metrics considered to verify the effectiveness of the PLM and QMS systems.

Table 4

Sl. No.	Matrices
1.	Reduce unrecorded changes < 5
2.	Reduce non-traceability of post-trial reports < 5
3.	Adhere to trial plan to 100%
4.	Ensure 100% updated ToT documents
5.	Reduce design errors < 5%
6.	Reduce unauthorized design changes to nil
7.	Meet customer requirements to 100%

E. Relation between PLM & QMS

The correlation between QMS and PLM specifically in the domain of new product development is studied. A clear understanding of the QMS & PLM and their interrelation will help, to orient the quality objective of the organization in the right direction.

The Hoshin Kanri [2] which is also known as the X matrix tool is used in this study to depict the relation between a) Stages in the New product development process b) ISO 9001:2015 clauses applicable to design and development c) PLM processes and features, d) Matrices to be improved.

The general structure of the x matrix is given in Fig.1.

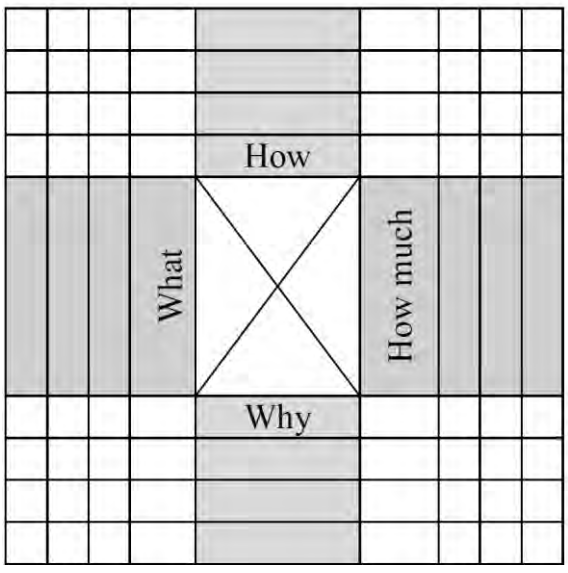

Fig. 1. General structure of the x matrix

It has four compartments – Why, What, How, and How much. Since the focus is to improve the product development area it is given in the 'Why' compartment. The ISO 9001:2015 clauses specific to product development are written in the 'What' compartment, Processes covered in PLM and features of PLM is given in the 'How' compartment

The study has been completed to understand the complete correlation among a) Stages in the New product development process b) ISO 9001:2015 clauses applicable to design and development c) PLM processes and features, and d) Matrices to be improved. The results are depicted in the X matrix. (Fig. 2).

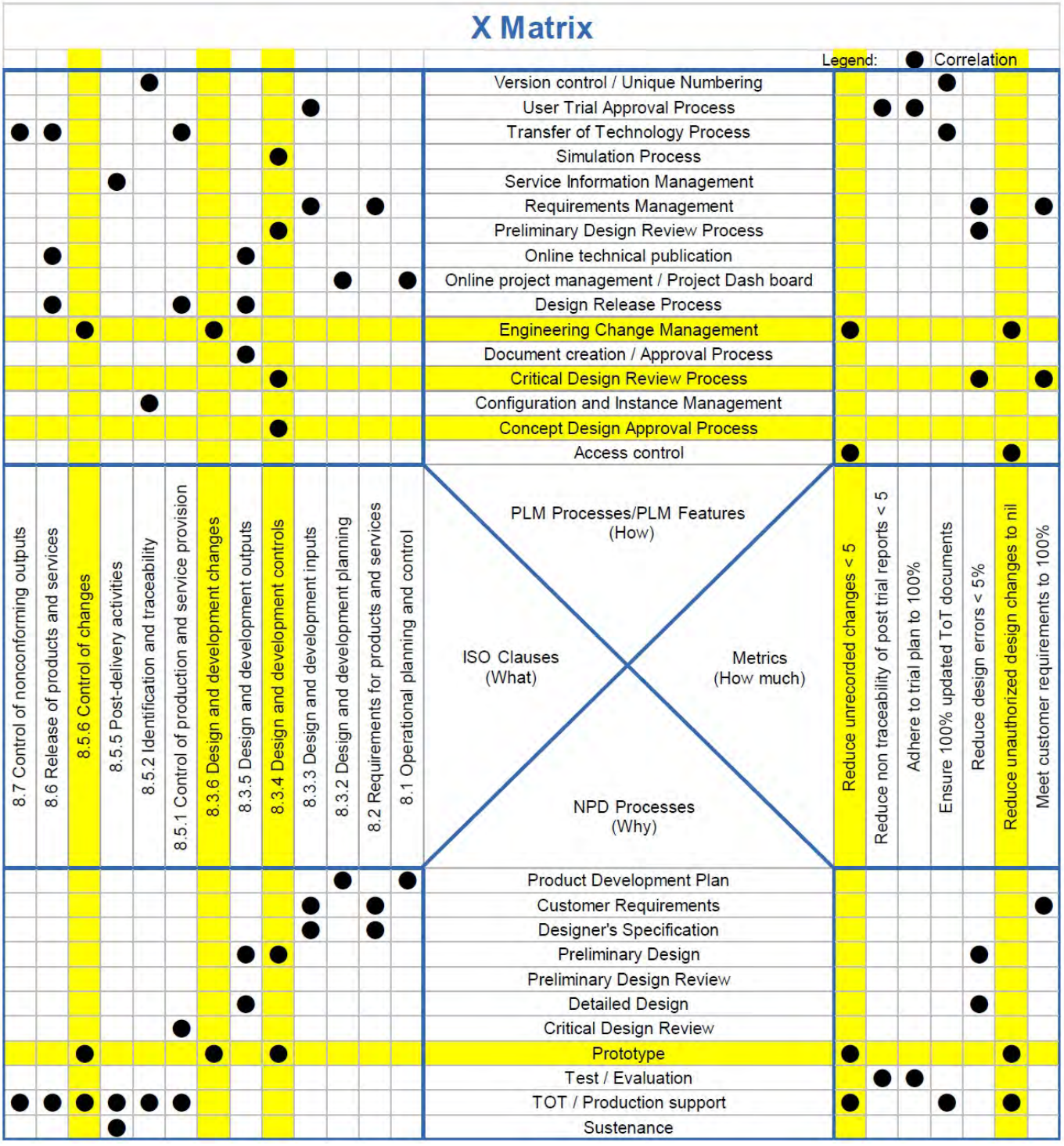

Fig.2. X-Matrix

The matrix clearly shows that the prototype development stage of NPD has a correlation with clauses 8.3.4 Design and development controls, 8.3.6 Design and development changes, and 8.5.6 Control of changes. Subsequently, clause 8.3.6 Design and Development changes have a correlation with the Engineering Change Management process of PLM. There are two metrics related to engineering change management. i) Reduce unrecorded change < 5, ii) Reduce unauthorized changes to zero.

III. RESULTS AND DISCUSSION

A. Efficiancy of the implementatiuon

The efficiency of the implementation is studied based on the manpower spent during ISO audit and preparation for the audit.

There are two types of Audit.

- Process based / project-based
- ISO Clause-based audit

The process or project-based audit is preferred over clause-based. PLM-assisted 'Audit ready' system assures confidence not only to auditors but also to review authorities at various levels.

Compliance to process is improved. Both PLM and QMS – ISO are complementary to each other. The integrated solution eliminates the deployment of unnecessary manpower in maintaining the ISO QMS system in place.

The below Pictures (Fig.3 & Fig.4) depicts benefits with respect to Audit preparations over several years. The 80% saving in man-days shown in the bar graph is a result of the integrated solutions.

The implementation of the PLM-QMS integrated systems has been completed in the year 2021. The savings in man-days spent on QMS activities has considerable reduced since after the implementation.

B. Effectiveness of the implementatiuon

The effectiveness of the implementation is estimated financially as follows as depicted in before and after the scenario.

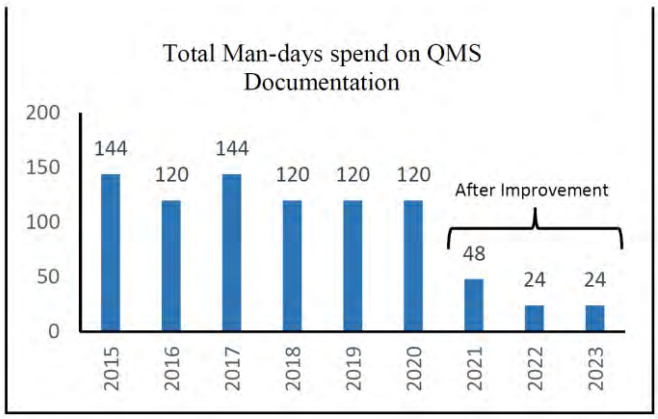

Fig. 3. Total Man-Days spent on QMS Documentation

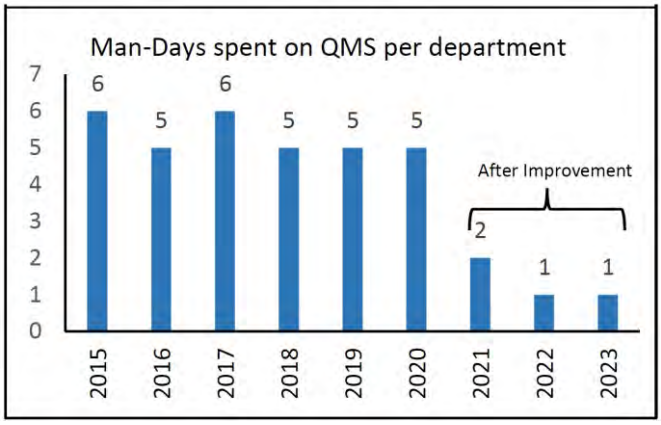

Fig. 4. Man-Days spent on QMS per department

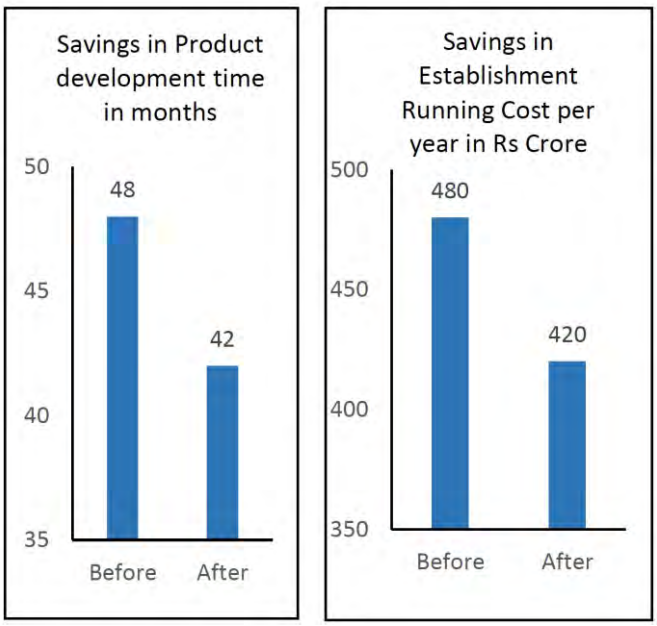

Fig. 6. Performance of ADVDL with engine failure

Adherence to ISO processes through PLM framework is estimated to have a saving of 6 months for the whole R&D Establishment considered. The

running cost saving is estimated as Rs 60 Crore / year. However, the implementation requires additional module that may cost Rs 50 lakhs per year. Considering the benefit we get, the additional investment is justifiable.

IV. CONCLUSION

The study reveals that the QMS system implemented through the PLM framework has significantly improved adherence to QMS standards, and the efficiency of the processes in the design and development area in meeting the organizational quality objectives. Additionally, the implementation also benefited considerable reduction in audit duration and improved the accuracy of QMS audit.

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We would like to express our sincere thanks to Director CVRDE for his continuous support throughout the work

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War Gaming Scenario Generation for Training and System Evaluation

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Abstract - War gaming scenario, also known as military simulation is a structured and interactive process that involves simulating military operations and engagements in a controlled environment. It serves as a tool for training, planning, and evaluating military strategies, tactics, and decision-making processes. It provides an opportunity for military personnel to practice and refine their skills in a simulated combat environment. This paper addresses the architecture of such war gamming scenario generation and how it is used for airborne sensor performance evaluation. It describes how two opposing forces build their own war gaming scenario based on their strategies. War gamming Scenario Generator has two parts, war gamming planning and scenario generation. War gamming planning involves defining geographical area, set operational boundaries and establish predefined conditions, specify participating forces, their composition and capabilities based on fidelity models. Real-time tactical and operational environments are made with the help of scenario generator. These environments, called scenarios, can contains various airborne, sea surface, ground and surface entities called targets. These targets can be associated with various attributes like radars, radios, missiles and other weapon systems. It also evaluates the airborne sensor performance. The representative airborne sensors that are considered are: Radar, Secondary surveillance radar, electronic intelligence and Communication intelligence. Measures of Performance (MOPs) of individual sensor against simulated scenario is an important feature of this simulation. It is used for the performance evaluation of the sensor under test. War gamming software is developed using C++ visual studio 2022 environment. It is using Microsoft Access and XML as backend database. It is developed using commercial software called 'STAGE' by extending its in-built simulation model; to incorporate War Gaming Simulation environment.

Keywords - Radar, SSR, COMINT, ELINT

I. INTRODUCTION

War gamming Scenario Generator provides an immersive and collaborative training environment for Armed forces. It allows individuals and teams to practice coordination, communication, and decision-making under simulated combat conditions. With the help of war gamming scenario generator module, Armed forces personnel creates their scenario base on mission planning and strategies. War gaming exercises foster teamwork, strengthen leadership skills, and improve interagency and multinational cooperation. Each scenario is built with a specific mission or set of objectives that the trainee must attempt to achieve. The mission could involve various military operations, such as offensive

manoeuvres, defensive actions, or intelligence gathering.

In system evaluation like airborne surveillance system where multiple sensors on board, war gaming scenarios play a crucial role in assessing the performance and capabilities of the sensor, technologies, and systems. By subjecting these systems to simulated operational conditions, scenarios enable the identification of strengths, weaknesses, and areas for improvement. System evaluation through war gaming scenarios helps inform procurement decisions, shape requirements for future systems, and optimize the utilization of existing assets.

II. LITERATURE SURVEY

In the following paragraph, we review the literature related to war gaming scenario generation and its application. Over the past years war gamming scenario generation is act as a decision-making simulation areas which help for mission planning and strategies. Alexandr Stefek et.al. [1], developed a Command and Control(C2) interactive war game simulation. The main task was to design and simulate procedures of C2 systems which correspond with real C2 structures including target detection, identification and assignment to unallocated fire unit (FU). Real time in-flight mission and sensor detection planning are described by Charles A. Leavitt [2]. How importance of Environmental effects on Airborne Radar Performance described by William A. Skillman [3]. Aircrafts Mission Planning and flight route are described by Stefek [4] and Jifang [5]. They also described how dedicated Flight planning tools can be used for effective Mission Planning. On the other hand, Hashir [7] described the key trade-offs in designing a scanning maritime radar with details of how the radar return can be simulated. Paul K Davis and Paul Bracken [8], highlights the selected challenges in developing AI models and decision aids in modeling, simulation and war gaming scenario. War gaming simulation can be combined with the airborne sensor simulation for the effective training.

None of the above literature was addressed as end-to-end War gaming scenario generation in dynamic airborne scenario. Literatures mentioned above does not cater for the scenarios where detection from multiple sensors is considered. This paper includes the design of War gaming scenario as well as airborne sensor detections in war gamming dynamic environment.

III. ARCHITECTURE

Our proposed war gamming simulator architecture is as shown in Figure 1. It supports multiplayer war gamming. Here multiple players belonging two opposite forces like red and blue forces team can participated with different station. In this architecture no limit on the number of players in red and blue forces teams. Both the forces trained in parallel for the different scenarios of war. Here war gaming controller is the master controller which controls the definition and execution of the simulation. It defines how the both forces participating in the simulation. It enables entire simulation management like resource allocation, viewing red force and blue force master together. It also selects the configuration of individual sensor simulators, including choice of simulation modes (with error etc.) and the configurable parameters. It has provision to schedule simulations at a later date or time. It also provides data analytics and consolidates reports about the simulation run or a set of runs to the administrator. Each forces have multiple specific role-based Scenario Generation Stations (SGS) and mission operator station (MOS) where trainee will be trained on specific sensor management and command and control (C2) related tactical skills. Trainee operator can use radios for communication among themselves for realistic training required for battle management.

The architecture of the war gamming simulator is as shown in figure 1.

A. War gaming controller

War Gaming Controller (WGC) is the main master controller and it is responsible for conducting the whole training exercise. It is monitoring health status of all subsystem like Blue-force SGS, MOS

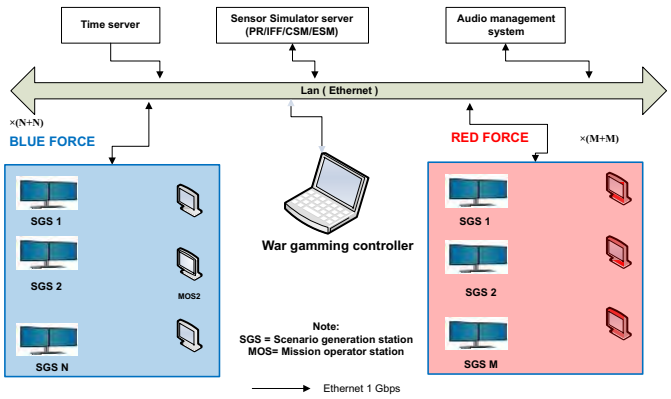

FIG 1: ARCHITECTURE OF WAR GAMMING SIMULATOR

station, Red-force SGS, MOS station and Sensor simulator server. It has 3 mode of operation Exercise Configuration, Activate Simulation and Replay.

i. **Exercise configuration mode** - In this mode WGC responsible for selecting the gamming areas ,Airbases and duration of the Exercise. It also configure no of participated players each Red force and Blue forces and master of each forces. In configuration mode, designating the Scenario Generation Station (SGS) from both the forces (Blue and Red-force) for specific roles such as Blue/Red force Master and slave stations for conducting the War Gaming exercise.

ii. Activate Simulation mode - Activate simulation mode will be activating in WGC station after receiving the acknowledge from each forces. Each forces planned their scenario and strategies according to assigned task given by exercise manager from WGC station and send acknowledgement to WGC station for start simulation.

iii. **Replay mode** -In replay mode trainees are able to replay the whole training exercise based on configuration setting in WGC station. Actual flight data can be replay in this mode. Based on actual flight data, simulated scenario is created and played in any of the Scenario Generation Station (SGS) based on configuration setting in WGC station.

B. Scenario Generation Station (SGS)

Scenario Generation station (SGS) is the station where both the forces (Red forces and blue forces) create their scenario and strategies based on task given by WGC station. In this station multiple databases can be created containing different platform, radars, radios, missiles, guns and other weapon systems etc. Using the databases various dynamic scenarios can be created which is used in the war Gaming simulation. It is developed using commercial software called 'STAGE' as a backend. Multiple entity with different dynamic as per sensor requirements can be simulate as a target with the help of this software. SGS enables the instructors to execute, control and monitor the training and conduct debriefing sessions. The SGS display consoles are able to show repeated display of the selected MOS consoles and allow the instructors to monitor and assess the task management skills of the individual mission operator trainee.

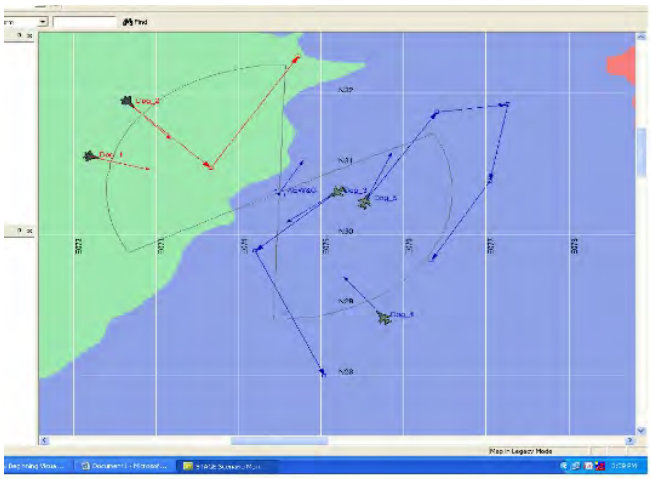

FIG 2: SCENARIO WITH TARGETS ALONG WITH OWNSHIP

C. Sensor Simulator server

Sensor simulator server contains all the required simulators of airborne sensors like Radar, SSR, ELINT and COMINT system. Scenario Generator sends targets information and Ownship platforms information to all sensor simulators. Here all the sensor simulator and scenario generator are time synchronized. The simulation models are decided based on the characteristics and specifications of the actual airborne system to mimic it as close as

possible. Design of the sensor model based on the modular architecture. Modular architecture is followed so that modules dedicated for dedicated tasks are implemented separately like module for different interfaces. Dedicated module is implemented to address the core functionalities of the sensors.

Based on war gaming scenario the detected target reports like Radar & SSR plots, ELINT emitter reports, COMINT emitter reports, are sent to the Mission operator station (MOS) for evaluate the mission operator performance.

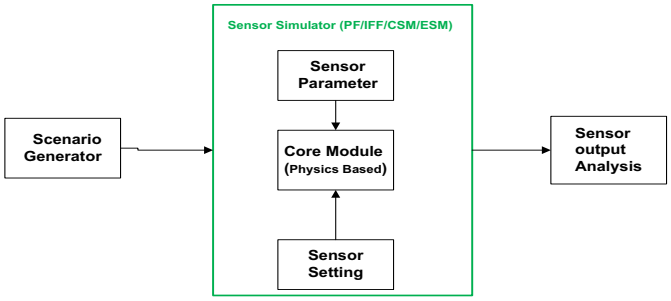

FIG 3: SENSOR MODEL ARCHITECTURE

D. Mission operator station
Mission operator station (MOS) enables to operate the mission systems (all the airborne sensor) in an identical manner with the same "look-and-feel" as on-board the aircraft. The mission operator interacts with a simulated environment planned and controlled by the instructor from the SGS. During training the mission operator can communicate with other mission operators as well as with the instructor of same forces via a dedicated intercom system

E. Audio management system
The Audio Management System will emulate the Audio Communication System on-board the airborne surveillance aircraft. The RF simulator with PTT simulates the RF communications between trainees, trainees and instructors or instructor to simulated pilot.

F. Time server
Time server is used for broadcasting the reference time for time synchronization among various subsystems of war gaming simulations. It broadcast time using NTP protocol. All the systems receive time either from broadcasted time or it can receive time based on query.

IV. FEATURES OF WAR GAMMING SCENARIO

Access to the SGS application is managed by the operator roles. These roles are a recommended division of responsibilities between the users. Following are the roles are defined in the SGS application to control the access to the application:

A. Database Administrator
Responsible for managing the basic and generic simulator database. DB admin's responsibility shall be to create platforms profiles, fixed points, special areas, generating standard routes and various tactical data items etc. as well as modify, update & deleting the scenario related data in database.

B. Planning Officer
Responsible for scenario mission planning which includes creating scenarios, adding simulated entities to scenarios, defining the simulated route by using waypoint or standard generic routes defined by DB Admin, generating the scenario and various tactical events like Aircraft take off & landing, setting transponder on/off, Aircraft Radar or Radio on/off, setting emergency transponder code to simulate emergency situation etc. Moreover, planning officer can pre-plan event to simulate Bombing and Time Over Target (TOT) and simulate the combat situation when the event gets executed during runtime.

C. Instructor/ Exercise Manager:
In charge of the required configuration design which includes scenario scheduling, resource allocation, loading and managing the current training session including adding runtime real time events (overall management of the current simulator activities). He is also responsible for the dedicated and personal training of the trainee and managing the current training session.

D. Simulated Pilot (SP):
Responsible for maneuvering the controllable

Simulated Entities (SEs) following the trainee's instructions. SP provides answers and reports which mirror those provided by pilots during actual missions.

E. Gaming Master:

Responsible for controlling the whole exercise in following ways:

i. Setting the Mode of training exercise i.e.
ii. Planning
iii. Simulation
iv. In Planning Mode, designating one of the SGS station for Mission planning among Blue-force SGS Stations similarly for Red-force SGS and Gaming area selection for entire training exercise.
v. In Simulation mode, designating the SGS and MOS from both the forces (Blue and Red-force) for specific roles such as Blue/Red force Master and slave stations for conducting the War Gaming exercise.
vi. Assigning the roles to all SGS and MOS station like Simulated Pilot, Instructor, Mission Controller etc.
vii. Monitoring the Blue-force Master and Red-force Master SGS stations, Health statuses of all subsystems, controlling the scenario simulation data sending to Sensor Simulators.

V. IMPLEMENTATION

The architecture of application in terms of implementation is based on Microsoft .Net Visual Studio 2019 and Qt 6.4. Minimum requirement to run the simulation applications is Quad-core processor with more than 8GB RAM and 500 GB hard disk with NVidia graphics card. Scenario database is housed in Scenario library located at server. The various view graphs are generated after the scenario generation and data analysis. War gaming scenario generation implementation includes following important steps:

a. First step is configuring the exercise. Selecting the gamming areas, Airbases and duration of the Exercise is done in this step. It also configures no. of participating players each red and blue forces and master of each force based on health of each subsystem. Configuration of resources for conducting War gaming exercise is based on health of each subsystem as shown in figure 4 and 5.

FIG 4: WAR GAMMING CONFIGURATION GUI

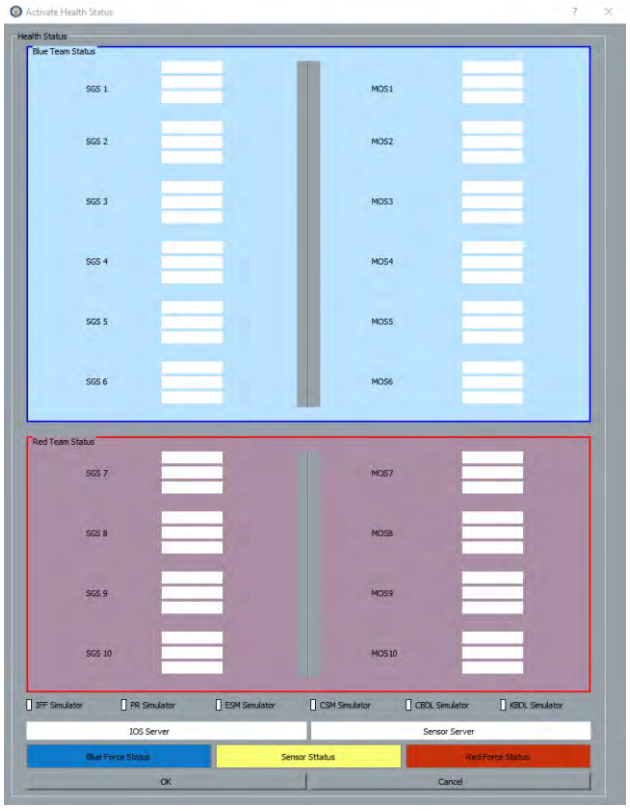

FIG 5: HEALTH STATUS OF SUBSYSTEM OF WAR GAMMING SETUP

b. Second step is planning the scenario according to WGC station in scenario generation station (SGS). Here, Red and Blue Team leader receive objective from WGC station and plan accordingly. After successfully planning a scenario, operator will inform to the WGC station.

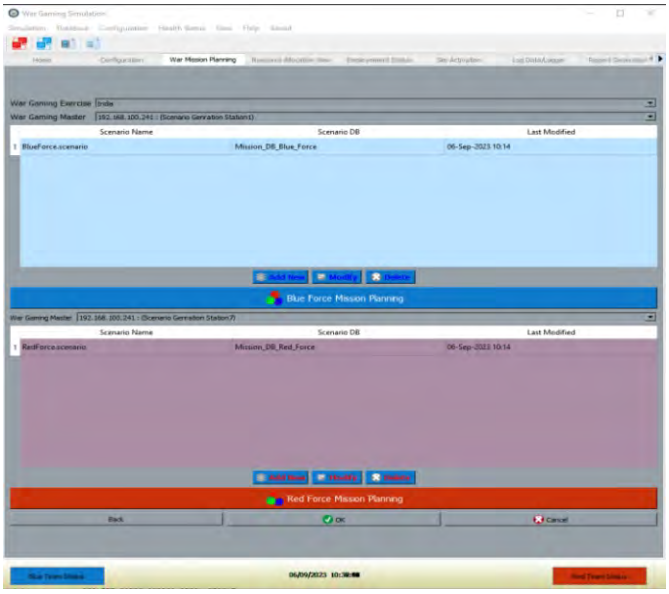

FIG 6: SCENARIO PLANNING IN WGC STATION

c. Third Step is Running of Simulation. After receiving the configuration both the force WGC station activate the simulation process.

FIG 7: ACTIVATION SIMULATION OF WAR GAMMING

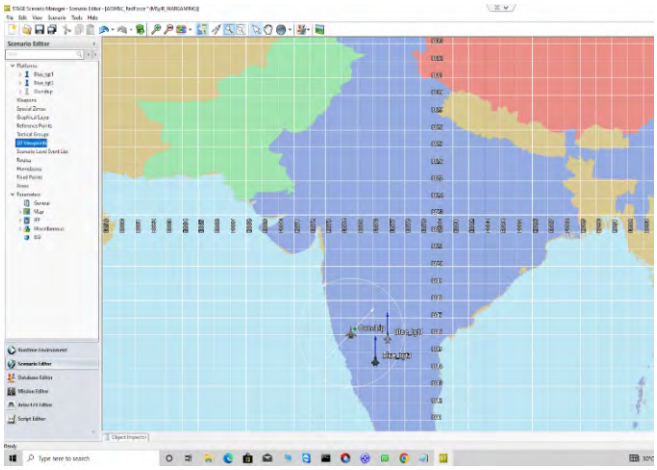

FIG 8: BLUE FORCE SCENARIO ACTIVATION

d. Next step is to record the whole training exercise. This is done in WGC station.
e. Last step is relaying the whole exercise. Here performance of both the teams can be judged based on their activity during exercise. With the help of replay mode team members get to learn their mistakes and become more skilled.

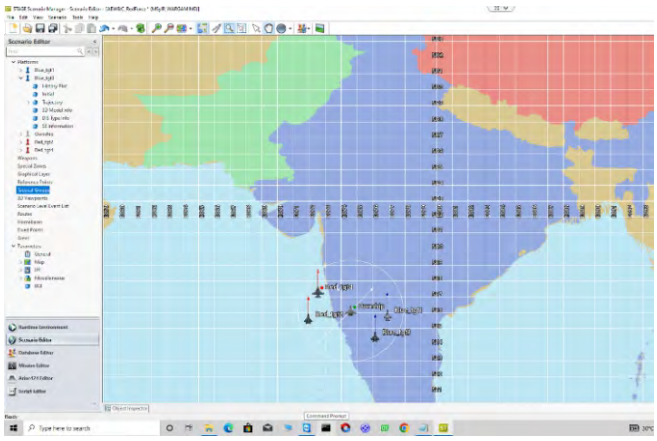

FIG 10: COMMON VIEW OF BOTH THE FORCES IN REPLAY MODE

VI. EFFECTIVENESS OF WGSG

Realistic and diverse scenarios play a crucial role in enabling effective training, planning, and evaluation in the context of war gaming. Here are some key reasons for their importance:

A. Realism in Training:

War gamming scenario generation helps to make realistic scenarios which provide a training environment that closely simulates the

complexities and challenges of real-world operations. By replicating actual operational conditions, including terrain, weather, and enemy behaviour, participants can experience the pressures and uncertainties they would face in actual combat. This realism enhances the effectiveness of training by allowing individuals and teams to practice and develop their skills in a context that closely resembles the operational environment.

B. Decision-Making Practice:
Diverse scenarios expose participants to a range of situations, each with its own unique set of challenges and constraints. This variety forces decision-makers to think critically, analyse options, and make informed choices. By encountering different scenarios, participants can refine their decision-making processes, assess the outcomes of their choices, and learn from the consequences. This practice enables the development of adaptive decision-making skills that are essential in dynamic and rapidly changing operational environments.

C. Tactical and Strategic Planning:
War gamming scenarios are made through invaluable for testing and refining tactical and strategic plans. They allow military planners to assess the suitability of various approaches and evaluate the potential effectiveness of different courses of action. By considering a range of scenarios, planners can identify strengths, weaknesses, and risks associated with their plans, enabling them to make adjustments and improvements before executing real-world operations.

D. Operational Evaluation:
Realistic and diverse scenarios provide a means to evaluate operational effectiveness and identify areas for improvement. By conducting war games with representative scenarios, military organizations can assess the performance of their forces, equipment, and tactics. The outcomes of these evaluations can reveal strengths and weaknesses, enabling adjustments to training, resource allocation, and operational plans. This iterative evaluation process facilitates continuous improvement and optimization of military capabilities.

E. Adaptability and Preparedness:
Realistic and diverse scenarios challenge participants to think creatively and adapt their strategies and tactics to dynamic circumstances. By exposing decision-makers to a variety of scenarios, including unconventional or unexpected situations, they are better prepared to handle unforeseen challenges in actual operations. This fosters flexibility, resilience, and readiness in the face of evolving threats and changing operational conditions.

F. Learning and Lessons Learned:
scenarios provide rich opportunities for learning and extracting lessons from war gaming exercises. After-action reviews and analysis of outcomes allow participants and organizations to reflect on their performance, identify best practices, and learn from mistakes. The insights gained from diverse scenarios contribute to a broader understanding of operational dynamics, leading to improved training methods, doctrine development, and organizational learning.

VII. CONCLUSION

War gaming scenarios and the associated simulation architecture provide a valuable tool for military organizations to enhance decision-making abilities, situational awareness, and critical thinking skills. Sensor simulators performance can also be evaluated using the war gaming simulation scenarios. By evaluating the performance of individual sensors against simulated scenarios, military planners can improve their strategies, tactics, and training methods.

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Digital Mock-Up Analysis inclusive of displacements in dynamic environment of Fighter Aircraft

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Abstract - Digital Mock-Up (DMU) focuses on geometric representations and clearance verification. DMU refers to the process of analyzing and evaluating the spatial requirements and constraints of systems using digital representations. The primary objective of the DMU is to identify any potential interference between components and to ensure sufficient clearance and spatial constraints between pipelines, structures and looms of aircraft systems, where accurate spatial planning and optimization are crucial early in the design stage.

Conventionally, DMU evaluation was conducted in static environment using aircraft Computer Aided Design (CAD) data. However, incidences of chafing marks were reported from operational aircraft even though aircraft was cleared with sufficient clearances in that zone in digital mockup and at build/pass-out stage. On further investigation, it has emerged that displacement due to vibration and maneuvering loads could be a cause for reduction of available clearance and led to chafing of pipelines as, DMU in static environment does not consider any displacement data caused by vibration and maneuvering loads. The conventional DMU evaluation process was unable to predict these issues under dynamic conditions. To overcome this limitation, DMU evaluation process was enhanced to Digital Mock-Up considering dynamic factors. By this enhanced process which incorporates displacement data caused by vibrations and maneuvering loads, the effects on the clearance between pipelines are determined and ensured whether safe clearance calculated in the static environment is still maintained under dynamic conditions. The assurance provided by considering Dynamic factors is valuable because it ensures that even if the initial clearances compromised due to vibrations or other dynamic factors, there is still sufficient clearance between pipelines to prevent intrusions and clashes.

Enhanced DMU evaluation process specifically considers the additional displacements due to random vibrations of each pipeline of unique material properties, diameter, length, support distance, thickness etc.

To effectively manage and incorporate the vibration data of individual pipelines with static DMU results, a program has been developed using Python programming language. This proactive approach enables to make necessary adjustments in the design stage itself to ensure proper clearance between pipelines, structures and looms; this improves overall safety and operational efficiency.

Keywords - Aircraft Digital Mock-Up, CAD, Dynamic Factors, Program Automation, Vibration

I. INTRODUCTION

The advent of Industry 4.0 has brought about significant advancements in aerospace manufacturing and design processes. With the integration of digital technologies, the aerospace industry leveraging tools such as Digital Mock-up (DMU), digital twin, augmented reality and many others to enhance product development and ensure optimal performance of complex systems, including fighter aircraft [1].

Within the aerospace domain, one of the pillars of digital twin technology is Digital Mock-up. The objective of the Digital Mock-ups is to ensure that all the components will fit together properly within the given space and there is no interferences (or) clashes between different components. Traditionally, physical mock-ups were used to verify the design, assembly and integration of various aircraft components. However, the emergence of digital mock ups has revolutionized this process by enabling virtual representation and spatial analysis of the aircraft structures, systems and subsystems in the design interface. By implementing DMU space analysis the aerospace industry aims to enhance the safety, longevity, and operational efficiency of fighter aircraft prior to production.

I. A. DIGITAL MOCK-UP (DMU)

Digital Mock-up (DMU) plays a crucial role in the spatial arrangement and evaluation of aircraft systems, particularly in the context of clearance/gap between adjacent pipelines, pipeline-to-structure and pipeline-to-looms interfaces [2][3]. By defining the standard clearance values based on design requirements and safety regulations, the DMU space analysis enables to verify if the actual clearances in the virtual model meet the standard requirements.

The digital mock-up allows detecting any clearance issues by identifying potential interferences or insufficient clearances, thereby helps to provide feedback to make necessary adjustments to the component positions, orientations or dimensions to ensure smooth integration, operation as well as safety of the aircraft.

Space analysis using digital mock-up aims in streamlining the design process and minimizing costly physical prototypes or rework. It facilitates the optimization of clearances without system malfunctions and ensures compliance with safety standards and regulations [2].

I. B. DMU IN STATIC CONDITION

Conventionally, Digital Mock-Up of fighter aircraft is carried out with Computer Aided Design (CAD) data irrespective of operational factors of aircraft, which is defined here as static space analysis. Static space analysis is effective for validating clearances under static conditions which does not consider the dynamic variations that occur during flight operations (shown in Fig.1). It is effective for validating the clearance between structures which are relatively static during operations. During aircraft operation, there are multiple factors such as random vibrations and maneuvering loads which may affect the DMU study results carried out with static CAD data. However, incidences of chafing marks were reported from operational aircraft even though aircraft was cleared with sufficient clearances in those zones. Conventional DMU evaluation process was unable to predict any issues under dynamic conditions (shown in Fig.2). To overcome these limitations, DMU space analysis in dynamic environment becomes crucial to account for factors such as random vibration and maneuvering loads experienced by the aircraft systems during flight[5].

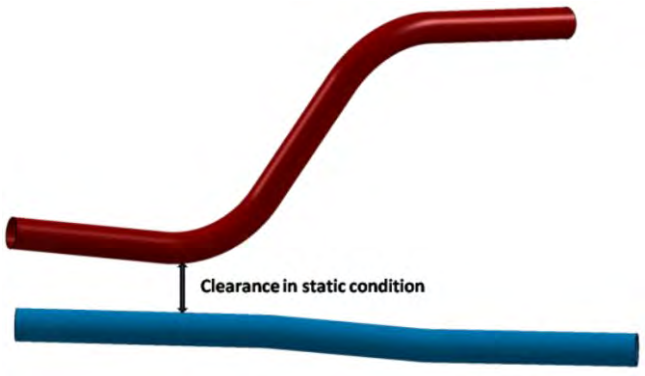

Fig.1. Clearance in static condition

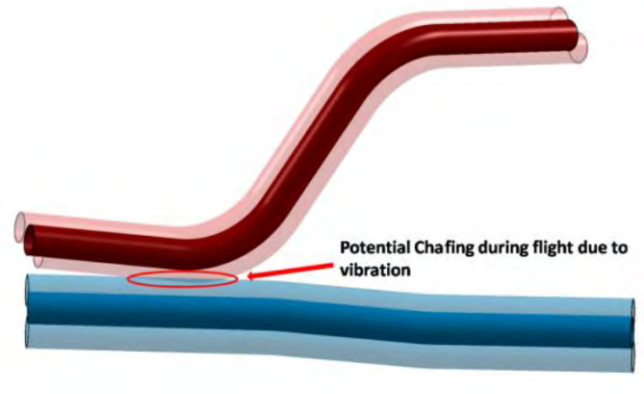

Fig.2. Potential chafing of pipelines during flight due to vibrations

II. DMU IN DYNAMIC ENVIRONMENT

DMU space analysis in dynamic environment considers dynamic factors such as random vibrations and maneuvering loads. The effects on the clearance between pipelines are determined by incorporating dynamic data and ensure whether safe clearance calculated in the static environment is still maintained under dynamic conditions [4] (shown in Fig.3). The assurance provided by considering dynamic factors is valuable because it ensures that even if the initial clearances are compromised due to vibrations or other dynamic factors, there is still sufficient clearance between pipelines to prevent intrusions and clashes.

DMU accurately assesses the clearance/gap between pipelines, adjacent components, and pipeline-to-looms. This evaluation helps to identify potential clearance issues that may arise during flight operations, enabling proactive measures to ensure optimal performance, safety, and longevity of the aircraft [3].

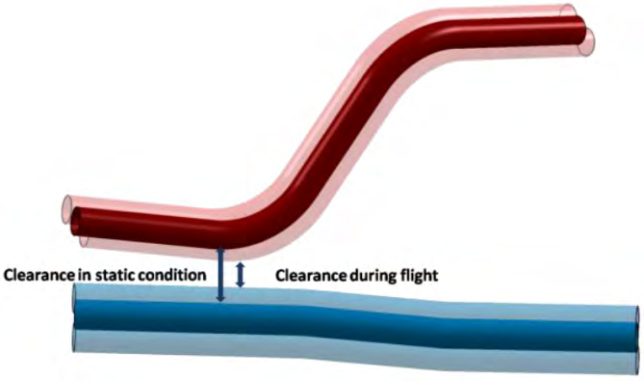

Fig.3. Clearance after displacement of pipelines due to vibration.

III. METHODOLOGY

Traditionally, DMU evaluation was conducted in static environment and the Static DMU Space analysis results of Components in aircraft with respect neighboring data were tabulated in an excel file (Table I) and studied without considering the vibration data caused by maneuvering loads. For enhancement of DMU inclusive dynamic factors, the vibration data of each pipeline are tabulated as Data base displacements from testing as shown in Table II. This approach is concentrated on pipeline displacements, hence displacement values for structures assumed as zero. To effectively manage and incorporate the vibration data of individual pipelines with static DMU results (Table I), a program has been developed using Python programming language. Static DMU results are the inputs for the program where it checks for the displacement of concerned pipelines (Product 1) in the vibration database which contains all the vibration data. This value is stored as 'Delta Displacement product 1' by the program. Similarly, the program checks the displacement for product 2 from vibration database. This value is stored as 'Delta Displacement product 2'. The sum of both the displacements of product 1 and product 2 is 'total displacement'. For ensuring permissible clearance between aircraft components even after vibration and maneuvering loads, during computing, the total displacement is multiplied by a factor of safety 1.25.

The 'Net clearance available' is the clearance compromised by dynamic vibrations of respective pipeline.

Net clearance available = Static environment value - Total displacement*1.25

Depending on this Maximum displacement value, the pipelines are classified as unsafe, critical and safe.

- If the max displacement value < 0, the clearance is unsafe.
- The max displacement value between 0 and 1, clearance is critical.
- The max displacement value between 1 and 3, clearance is less than 3mm

- The max displacement value > 3, the clearance is safe.

The program will generate the excel sheet accordingly.

TABLE I. DMU RESULTS IN STATIC CONDITION

Sl. No.	Product 1	Product 2	Type	Value	DMU Remark
1.	Pipeline	Structure	Clearance	1.7mm	Clearance is less than 5mm
2.	Pipeline	Std part	Contact	0mm	Contact issue
3.	Pipeline	Pipeline	Clearance	3.2mm	Clearance is less than 5mm

TABLE II. DATA BASE DISPLACEMENTS FROM TESTING

Sl. No.	Part No.	Materials	Diameter (mm)	Support distance (mm)	Total Displacement (mm)	Total Displacement*1.25 (mm)
1.	Pipeline 1	Stainless Steel Tube	25	350	0.5829	0.7286
2.	Pipeline 2	Stainless Steel Sheet	63	250	0.8447	1.0559
4.	Pipeline 3	Al Alloy Tube	06	450	0.5000	0.6250
4.	Pipeline 4	Al Alloy Tube	25	250	0.2422	0.3028
5.	Pipeline 5	Ti Alloy	10	1150	0.2704	0.3380
6.	Pipeline 6	Ti Alloy	16	150	0.2207	0.2759

TABLE III. DMU RESULTS IN DYNAMIC ENVIRONMENT

Sl. No.	Static Environment-Values from CATIA geometry					Dynamic Environment(Additional displacement due to vibrations and inertial loads)			Net clearance Available (X-Y)	Status
	Product 1	Product 2	Type	Value (X)	Remarks	Delta Displacement Product1	Delta Displacement Product 2	Total Displacement (Y)		
1.	Pipeline 1	Structure	Clearance	1.7mm	Clearance is less than 5mm	0.7286	0	0.7286	0.9714	Critical
2.	Pipeline 2	Std part	Contact	0mm	Contact issue	1.0559	0	1.0559	-1.0559	Unsafe
3.	Pipeline 3	Pipeline	Clearance	4.5mm	Clearance is less than 5mm	0.6250	1.0559	1.6809	2.8191	Clearance is less than 3mm

```
for i in range(len(inp_file1['SL.No.'])):
    if inp_file1['Maximum Displacement'][i]<0:
        inp_file1['status'][i] = 'Unsafe'
    elif inp_file1['Maximum Displacement'][i]>=0 and inp_file1['Maximum Displacement'][i]<=1 and inp_file1['Displacement Sum'][i]!= 0.0:
        inp_file1['status'][i] = 'Critical'
    elif inp_file1['Maximum Displacement'][i]>=0 and inp_file1['Maximum Displacement'][i]<=1 and inp_file1['Value'][i]==0:
```

Fig.7. Portion of Python program

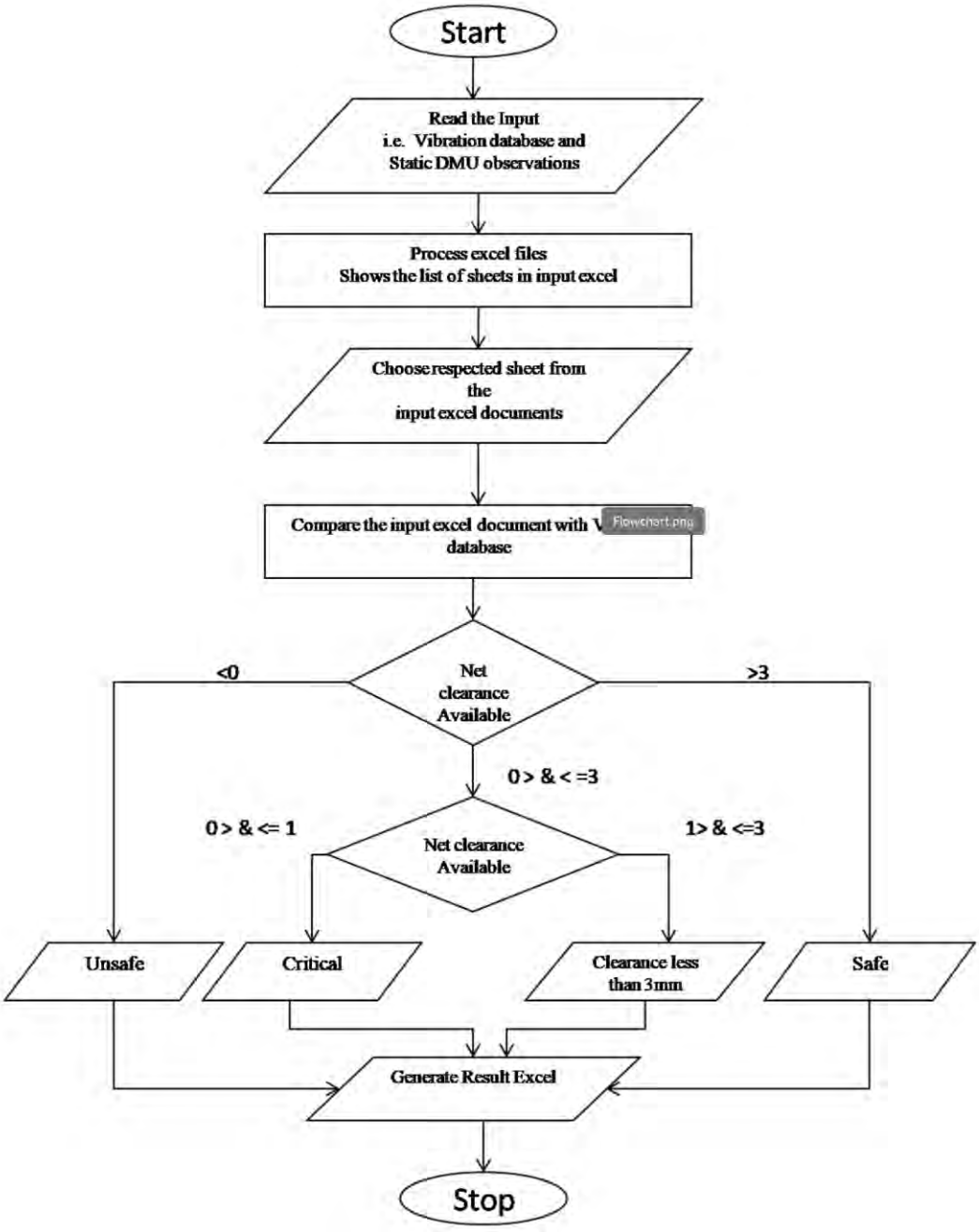

Fig.5. Pictorial representation of python program

IV. RESULT

DMU IN DYNAMIC ENVIRONMENT- INFERENCE

The CAD data of aircraft as shown in Fig.4 shows the complexity of design data including different systems such as structure, system pipelines, Line Replaceable Units (LRU) etc. To understand DMU process in dynamic environment, let's consider two neighboring pipelines have additional displacements due to vibration. The vibration zone of each pipelines are colored RED as shown in Fig.5. DMU validation process in dynamic environment examines and ensures the guideline clearance available even after considering displacement due to vibration. After satisfactory result, DMU clearance is obtained for production of system pipelines and structure components. The image of physical aircraft pipeline routing is shown in Fig. 6.

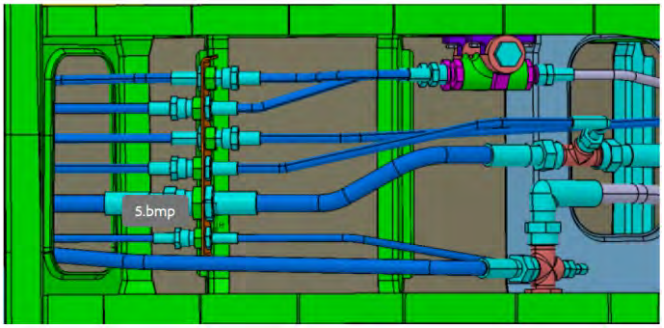

Fig.4. CAD image of pipeline routing in static condition

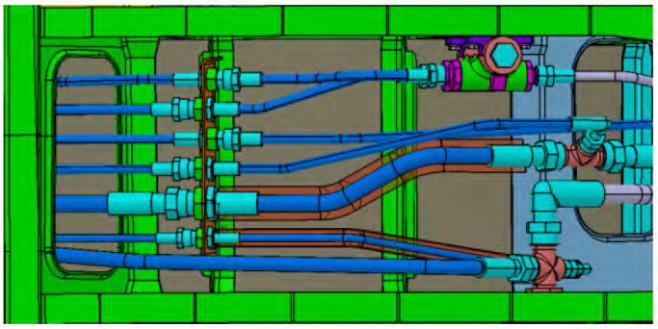

Fig.5. CAD image of pipeline displacement due to vibration

Fig.6. Routing of pipeline during production post DMU

V. ADVANTAGES OF ENHANCING DIGITAL MOCK-UP IN DYNAMIC ENVIRONMENT

1. Clash Detection: The clash analysis in dynamic environment helps to identify any instances where pipelines from different systems come too close or chafe/rubbing with each other during operations due to dynamic factors. Potential clashes can be identified and resolved before manufacturing or installation.

2. Clearance Analysis: The clearance analysis in dynamic environment helps to ensure adequate space between pipelines and other components or structures even after the clearances compromised by dynamic factors.

3. Iterative Design Optimization: Optimizing the design of pipelines and their routing within the aircraft. By virtually modifying the positions, routing, or support structures of the pipelines, DMU can be used to analyze and evaluate the resulting clearances in real-time to achieve the adequate clearances.

4. Digital Mock-Up in dynamic environment minimizes the maintenance overheads by reducing the need of inspection of critical zones in every service cycle. Thus, the use of Digital Mock-Up in dynamic environment helps reduce costs, and risks associated with physical prototyping. It allows optimization of the aircraft's design, leading to safer more efficient and reliable aircraft.

CONCLUSION

In conclusion, the integration of DMU space analysis in dynamic environment ensures meticulous scrutiny integration. Furthermore, DMU space analysis in dynamic environment has emerged as a vital component, addressing dynamic properties such as vibrations, which allows for proactive evaluation of clearance variations. This approach greatly contributes to improved safety, performance, and longevity of fighter aircraft. The utilization of a Python program for data processing and comparison significantly enhances the accuracy of clearance analysis, ensuring compliance with safety standards. This commitment to precision further solidifies the industry's dedication to maintaining the highest levels of safety and operational excellence. The comprehensive approach, which combines both static and dynamic space analyses, enables thorough evaluation of geometric and dynamic aspects of aircraft systems. As a result, it minimizes the risk of clearance issues and operational challenges, ultimately leading to increased operational efficiency and reduced maintenance requirements. The ongoing exploration and refinement of these technologies will pave the way for a safer, more efficient, and technologically advanced future in fighter aircraft

development. By embracing DMU space analysis in dynamic environment in the aerospace industry is poised for continuous progress in enhancing design excellence and adherence to stringent safety standards.

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Augmented Reality based Mobile App in Aircraft Applications

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Abstract - In this paper, we present an augmented reality based mobile or tablet android app for maintenance of the aircraft. We have created a graphical user interface of augmented reality based android mobile or tablet app which contains the menu for selection of different user conditions as per requirements of aircraft technician on field. The android mobile app demonstrates the user interactive features of image, ground plane and 3D model mapping and detection for augmenting the digital content of aircraft systems. It demonstrates the assembly and disassembly of landing gear and wing structures in the aircraft.

This AR mobile app is used to assist and train aircraft technicians about the maintenance activities in their handheld mobile or tablet devices. The feedback from scientists working in the domain of aircraft design and maintenance applications confirms that such mobile apps based on augmented reality have good future scope for aerospace and automobile industries, especially for training and the maintenance activities.

Keywords - Aircraft, Assembly, Augmented Reality, Disassembly, Maintenance, Unity 3D, Vuforia

I. INTRODUCTION

Now a days the increasing growth of global aviation industries makes the demand of safety in aviation a significant concern. [1]. The root causes of aviation accidents have been recognized in order to lessen their frequency. The root causes include human error, mechanical failure, hazardous weather, sabotages and military operations [2]. Around 75 percent of aviation accidents are caused by mistakes made by humans or human errors. In aircraft maintenance, the technician completes a challenging repair or inspection task under limited time and with minimum feedback, this is when human error occurs in maintenance activities [3]. As mistakes made by humans in maintenance creates a risk to the safety of aircraft, numerous automated tools and simulation techniques have been developed to reduce the chance of human error [4].

The aircraft technicians conduct routine maintenance of aircraft systems, at such times aircraft technicians refers to the manual of that specific aircraft to get detailed instructions and step by step procedures. A lot of time is generally used to just searching for the steps to be followed in maintenance activities of specific system, which results in increased time for maintenance, decrease in performance with stress to technicians.

The use of computer-based tools like Augmented Reality (AR) devices in maintenance of aircrafts are added the interest of researchers in aviation sector. Augmented reality is a technology that combines real world surroundings and digitally produced virtual data. With implementing augmented reality, the necessary information may be accessible when it is needed, increasing the productivity of the aviation maintenance system [5]. Augmented reality makes system simple to obtain and understand information in the form of text, visuals, sounds, or animations [6].

The aircraft technicians conduct routine maintenance of aircraft systems, at such times aircraft technicians refers to the manual of that specific aircraft to get detailed instructions and step by step procedures. A lot of time is generally used to

just searching for the steps to be followed in maintenance activities of specific system, which results in increased time for maintenance, decrease in performance with stress to technicians. When working with the AR devices in aviation maintenance, the technician can refer to the detailed instructions as per maintenance manual of aircraft systems. With such, when conducting maintenance tasks, technician can reduce head and eye movement, switching between contexts, and transitional times for repairing operations [7].

The goal of this study is to create an AR mobile application that demonstrates the training of technicians, process of assembly and disassembly using human interactions and animations of the aircraft systems, example landing gear.

II. RELATED WORK

A. Aircraft Maintenance with AR based Mobile Apps

For aircraft maintenance, multiple research scholars from academia and industries have created augmented reality based mobile applications. An application of AR has been proposed by Crescenzio et al. for the oil check maintenance work of aircraft Cessna C 172P [8]. An augmented reality application for removing and installing of landing gear pitch trimmers was created by Jo et al. [9]. Henderson and Feiner designed an augmented reality application for the Rolls-Royce Dart 510 turboprop engine's combustion chamber maintenance [10].

The augmented reality based mobile applications listed below in table I are examined to determine their prospective usability rate in terms of their layout, usability, graphical user interface, design of interactions, and activities.

According to the above-mentioned researchers, implementing augmented reality in training and aircraft maintenance reduces stress at work and maintenance time of technicians. This suggests that it is appropriate for applying AR in aircraft maintenance. Therefore, the use of augmented reality can be expanded with human interactions to training and aircraft maintenance tasks [16], for example like aircraft landing gear assembly and disassembly.

TABLE I
IAR BASED MOBILE APPS IN AIRCRAFT MAINTENANCE

Sr	AR Application	Devices	Operations	Efficiency	Remarks
1	GMF 4.0 - Aeroasia Training AR [11]	Smart phone and tablet	Step to step procedure	Improve human error	Training. 3D model with animation
2	MRO AIR-Artificial Intelligent Reality [12]	Smart phone and tablet	Collaborative experience	Real time pointing	Aircraft repair. Voice call assistant
3	PTC - Cirrus Aircraft Aviation Maintenance [13]	System Application through camera	Informative based concept	Advanced learning experience	Training. Look around the 3D model
4	Heartwood - AR for Operation Training [14]	Android and Apple devices	Google AR Core features	No need a specific marker to trigger	Training. High light situation support
5	AerinX-Smart Inspection [15]	Drone with camera	Scan for blind spot damage or deflection	Extend the range of object recognition by drones	Smart Inspection. Airframe structure scan

III. METHODOLOGY

This section is divided into two sections, first as the creation of the AR application with Unity 3D [17] and second as demonstration of the AR based mobile application.

A. AR App Development with Unity and Vuforia

We have created the android application with the help of Unity 3D software with Vuforia plugin for augmented reality-based maintenance of aircraft industries. The image target feature is for detecting and tracking of images by comparison of features from camera image with known target image from database. The area targets that track and augment the spaces and areas with feature of environment tracking. The use of ground plane feature in Vuforia and with Google AR core has been explored for development of feature detection in digital content. The ground plane stage set aside aircraft content to be positioned relative to the ground plane itself, so that allowing us to place

the aircraft content relative to the real-world aircraft surfaces and scale it. For scaling and aligning the digital content with real ground plane, we have used same physical properties such as dimensions and mass to the digital world content and aligned to ground marker. The user interface for the unity with ground plane feature is shown as below in figure 1.

We have explored the model target feature of Vuforia for augmenting the digital content on real

Fig. 1. Unity Interface for App Development with Ground Plane

world scaled aircraft model data. The model targets enable AR app to recognize and track aircraft structure parts / objects. The major challenge to that affects the tracking quality is to match the physical dimensions (length, width, and height) with respective dimensions of real-world objects.

As aircraft system components are large scale real objects, we have scaled down the dimensions to match the real-world components when using in the aircraft AR mobile app. The model target generator generates model targets by taking a 3D model of aircraft to track as input and feedback. To make a model target for an aircraft, we have 3D

Fig. 2. Unity Interface for App Development with Model Target

printed to aircraft CAD model with scaling. An user interface with model target feature is shown as below in figure 2.

B. Demonstration of AR based Mobile Application

The AR mobile app explores the user interface of buttons and touch interactions to digital content of aircraft in augmented world. The image target menu represents images that AR app can detect and track it. The AR app detects and tracks the image by comparing extracted natural features fromthe camera image against a known target image resource database which we have defined while creating the application. Once the image target is detected, app will track the image and augment aircraft system information in AR world. The human interactive user interface of mobile app is shown below in figure 3

Fig. 3. AR Mobile App User Interface

In ground plane target menu, we have added the feature of digital content to be positioned relative to the ground plane itself with an interaction of touch to move and rotate the digital content, which is augmented in real world, as shown in below figure 4..

Fig. 4. AR Mobile App Demonstration with Aircraft on Ground Plane

The aircraft model menu explores about augmenting the digital content on real aircraft system data. We have 3D printed the scaled components of aircraft systems with Polylactic Acid (PLA) filament by using Creality sermoon D1 3D printer. The 3D printed aircraft model was trained for feature detection with the help of model target generator of Vuforia by taking a 3D model feature of aircraft to track as input with scaling. The model target is made with different guide views for effective tracking of aircraft components from different angles. The model target tracking works best if the aircraft is static and does not move after detected.

In the augmented reality world, we have demonstrated the assembly and disassembly with step-by-step procedure of maintenance in the form of messages, videos, animations (translations and rotations) of aircraft components in the AR mobile app. With such mobile app, the aircraft technicians get interactive learning and assistance in augmented reality world within time. AR mobile user interface and interactions with the aircraft systems with model target are shown in below figure 5.

Fig. 5. AR Mobile App Demonstration with Aircraft on Model Target

IV. RESULTS AND DISCUSIONS ON AR MOBILE APP

The AR mobile app is useful with training of new technicians who are undergoing learning of aircraft systems with interactive way in augmented reality world and collaborative ways of training [18]. With the help of usability evaluation tools like cognitive loads, NASA TLX and System Usability Scale (SUS), we are planning to check the effectiveness of the augmented reality based mobile application being developed for aircraft maintenance as per human factors in aviation [19].

The ground plane feature of AR app is only compatible with devices supported by platform enablers (ARKit /ARCore) or devices. For good results of feature detection and tracking of model target, aircraft system model is kept static and no movement of it after detected.

V. CONCLUSIONS

Augmented reality (AR) is an immersive practice of developing the real world and virtual environment to create combined visual surroundings which can act as effective augmenting way various fields in education, aircraft to health care sector [20]. We have created the user interactive mobile application which is helping the aircraft technician for training and day to day activities in aircraft maintenance with effective human interactions in the world of augmented reality. Such an augmented reality-based activities maintain a high standard of safety that minimizes safety related incidents and accidents.

In future, we are going to add the usability evaluation tools like cognitive load, NASA TLX and System Usability Scale (SUS) with geometrical model mapping feature for object detection and feature like remote assistance in real time with digital twins of aircraft system.

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Building Augmented Reality Application for Real-Time Aircraft Components Identification

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Abstract - Augmented Reality (AR) technology combined with Computer vision has gained significant attention for its potential use in various applications. Our focus in this paper is in implementation of this technology for fighter aircraft in Daily Inspection and maintenance Process. It enables the faster training of the technicians and guides them in giving the stepby-step instructions. This paper presents the AR application that enables the real-time aircraft component detection and labelling and upon selecting it can display further info and can attach any simulation if available. To ensure robust performance, a customized image dataset is created with label/annotations using the specific aircraft 3D CAD assemblies/parts, against the more general pre-trained dataset like ImageNet, MS COCO etc. By this customized dataset; object detection is made with TensorFlow object detection framework using Convolutional Neural Network using MobileNet architecture for classification and SSD (Single shot detector) for detection. The dataset can be further improved with the labelled images taken from the real aircraft. The dataset and the algorithm can be validated with the sample video taken from the real world aircraft or virtual aircraft, and overlaying the identified labels on the frame-by-frame video being played. The specially developed AR android UI/UX app on tablet, when focused on real aircraft, will detect the aircraft component in real-time and overlay the label in right place. Further it can display the detailed description by textual/video/audio, on selection, about the component. This work can be further extended by taking this as foundation model for building real-time Augmented Reality Applications for model target and overlaying the 3D CAD model on physical aircraft which improves the intractability and helps in addressing design issue and component maintenance.

Keywords - Real-Time Object Detection, TensorFlow Object Detection, OpenCV, Synthetic Dataset, Unity Game Engines, frontend application, Android UI/UX, Augmented Reality.

I. INTRODUCTION

The convergence of Augmented Reality (AR) technology and Computer Vision has emerged as a pivotal area of research, offering a multitude of applications across diverse domains. This synergistic integration has garnered significant attention due to its potential to revolutionize various industries. This paper focuses on harnessing this combined potential in the realm of fighter aircraft maintenance and daily inspection processes. By leveraging AR technology in conjunction with advanced computer vision techniques, we aim to expedite technician training and streamline maintenance procedures.

The primary objective of this study is to present an innovative AR application tailored to the unique demands of the aerospace industry. This application empowers technicians with real-time aircraft component detection and precise labeling. Moreover, it provides step-by-step guidance, enhancing operational efficiency. Notably, the AR interface facilitates access to comprehensive information about selected components, including the incorporation of simulations where applicable.

In order to further refine our dataset, we supplement it with labeled images obtained from actual aircraft inspections. Validation of both the dataset and algorithm is conducted through the analysis of sample videos, captured from real-world or virtual aircraft environments. The identification of labels is superimposed onto frame-by-frame video, providing tangible evidence of the system's proficiency.

The culmination of this research effort is manifested in a bespoke AR Android application, designed with a user-friendly interface and intuitive user experience (UI/UX) on a tablet platform. When focused on a real aircraft, this application adeptly detects aircraft components in real-time and overlays accurate labels in their designated positions. Additionally, upon selection, the application can furnish detailed descriptions via textual, video, or audio formats. Looking ahead, this foundational model serves as a springboard for further advancements. Future endeavors will involve the integration of real-time AR applications for model targeting, affording the capability to overlay 3D CAD models onto physical aircraft. This innovative approach promises to enhance interactivity and address critical design considerations and component maintenance procedures. This introduction provides a comprehensive overview of the research, highlighting the integration of AR and Computer Vision, the specific focus on fighter aircraft maintenance, and the innovative methodologies employed in dataset creation and algorithm validation.

II. LITERATURE SURVEY

This literature survey, features work by various authors, provides insights into the dynamic landscape of computer vision for object detection, and enables the usage of augmented reality applications across diverse domains. It initiates with "Automatic 'Ground Truth' Annotation and Industrial Work piece Dataset Generation for Deep Learning" [1], where automated approaches are developed for generating "ground truth" annotations and work piece datasets, showcasing the pivotal role of computer vision. In "Automotive Parts Assessment: Applying Real-time Instance-Segmentation Models to Identify Vehicle Parts" by [2], real-time instance segmentation models are harnessed to identify vehicle parts, elucidating the fusion of computer vision with object detection techniques for automotive parts assessment. Furthermore, "Semantic object classes in video: A high-definition ground truth database" by [3] illustrates the intersection of computer vision and video analysis with the creation of high-definition ground truth databases for semantic object classes. The integration of synthetic data into object recognition pipelines, as explored in [6] "Synthetic Data Generation to Speed-Up the Object Recognition Pipeline," signifies the pivotal role of computer vision in dataset augmentation and accelerated model training. In the context of urban surveillance, [7] "Vehicle Detection by Fusing Part Model Learning and Semantic Scene Information for Complex Urban Surveillance" explores the fusion of part model learning and semantic scene information, leveraging computer vision for advanced vehicle detection. Lastly, the amalgamation of deep learning and augmented reality in engineering lab training is showcased in [8] "Deep-Learning-Incorporated Augmented Reality Application for Engineering Lab Training," signifying the synergy between computer vision and augmented reality, revolutionizing training, and education practices. Collectively, these references underscore the far-reaching impact and versatility of computer vision, object detection, and augmented reality technologies in industrial, automotive, and educational applications.

III. METHODOLOGY

To ensure the robust performance of our system, we emphasize the creation of a customImage dataset, enriched with precise labels and annotations. This dataset is meticulously crafted using 3D CAD assemblies and parts specific to the target aircraft. This approach distinguishes itself from more generic, pre-trained datasets like ImageNet or MS COCO. Employing TensorFlow object detection with pre-trained model (SSD MobileNet V2 FPNLite 320x320 model) using transfer learning and loading the trained model into unity 3D environment for building the interactive augmented reality application. The framework of AR Application followed in this paper is given in Fig. 1.

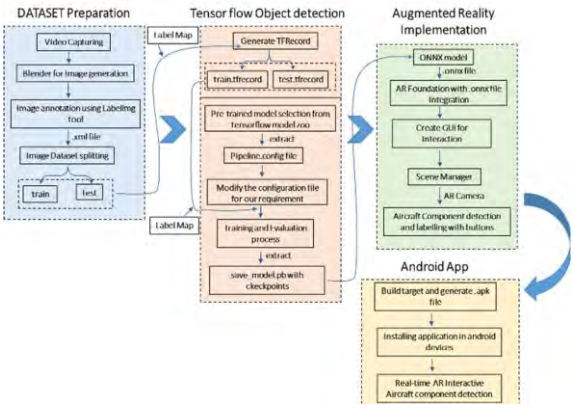


Fig. 1. Framework of AR application for real time aircraft components labelling

A. Dataset

3.1. Dataset Preparation:

3.1.1. Capturing video and Image generation

Capturing video footage of fighter aircraft. Ensure that the video is recorded under well-lit conditions and at various angles to capture different components. Generated the Images by importing the video in Blender and exported by image render.

3.1.2. Annotation of Aircraft Components

We employ labelImg to annotate the aircraft components in the images, ensuring that each component is properly labelled. LabelImg is a lightweight and easy-to-use image annotation tool to label object class by bounding boxes in images. It is a free, open-source software program for labelling images using graphs.

3.1.3. Labelling Process

Load each image into the LabelImg tool and draw bounding boxes around the aircraft components. We have assigned labels for 11 Aircraft components (i.e., Cockpit, Radome, IRST, Refuelling Probe, Canard, Air Intake, Drop tank, Missile, Airbrake, Vertical Fin, Engine Nozzle) by drawing bounding box and save the file as (.xml) as shown in Fig. 2.

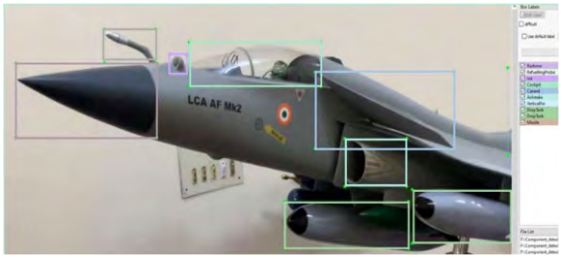


Fig. 2. Annotating Aircraft image using LabelImg tool

3.1.4. Splitting Image data

Divide the annotated dataset into two distinct subsets: a training set and a testing (validation) set. The common split ratio used is 75% for training and 25% for testing, but this can vary depending on dataset size and model accuracy.

B. Object Detection

3.2. TensorFlow Object Detection

3.2.1. Label Map generation

Creating a labelmap.pbtxt file is crucial for mapping class labels to integer IDs. Each aircraft component class should have a unique integer ID associated with it. Ensure that the label_map.pbtxt file adheres to the correct format, with each class entry specifying both an ID and a name in the dictionary data structure.

3.2.2. TFRecord generation

Convert the annotated dataset into TFRecord format, which is a binary format suitable for efficient input to TensorFlow. TensorFlow object detection provides scripts and tools for this purpose. Create separate TFRecord files for both the training and testing datasets. These TFRecords should include image data along with corresponding annotations, such as bounding boxes and class labels.

3.2.3. Model Selection from TensorFlow model zoo

Explore the TensorFlow model zoo to select an appropriate pre-trained object detection model. Comparison of pre-trained models in TensorFlow model zoo with inference speed and mean average precision based on MS COCO. These models vary in complexity, accuracy, and speed as shown in Table below.

TABLE I. COMPARISON OF PRETRAINED MODELS

Model Name	Variation of model		
	Speed(ms)	COCO mAP	Output
SSD MobileNet V1 640×640	48	29.1	Boxes
SSD MobileNet V2 FPNLite 320×320	22	22.2	
SSD MobileNet V2 FPNLite 640×640	39	28.2	
SSD ResNet50 V1 FPN 640×640	46	34.3	
Faster R-CNN ResNet101 V1 640×640	55	31.8	

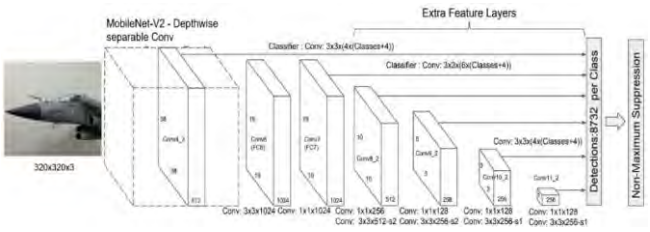
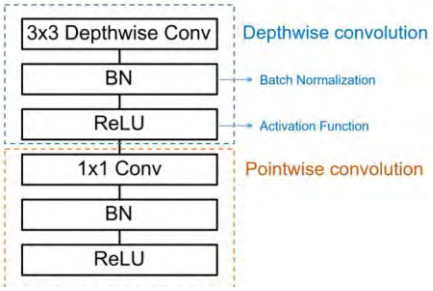


Fig. 3. Framework of AR application for real time aircraft components labelling

Based on our specific requirements and hardware constraints, chosen SSD MobileNet V2 FPNLite 320x320 model that strikes a balance between accuracy and inference speed. This model is a solid starting point as shown in Fig. 3.

The objective is to achieve object detection across eleven aircraft component classes. Therefore, the deep neural network model, which is built upon the MobileNet-SSDv2 architecture, which is lightweight, low latency and low power with good detection speed (22ms with MS COCO) and easy to deploy in mobile. This model combines MobileNet-v2 as the underlying network backbone, incorporates the Single Shot MultiBox Detector (SSD) for precise object detection, and integrates a Feature Pyramid Network (FPN) to enhance feature extraction capabilities.

The MobileNet model is based on depth-wise separable convolutions, which is a form of factorized convolutions that factorize a standard convolution into a depth-wise convolution and a 1×1 convolution called a pointwise convolution. The depth-wise separable convolution splits this into two layers, a separate layer for filtering and a separate layer for combining. This factorization has the effect of drastically reducing computation and model size. MobileNet uses the activation function ReLU that has the property to handle the non-linearity and solves the vanishing gradient problem. Batch normalization is done to regularize the weights to improve stability of model through normalization of the layers input by re-scaling. It uses SoftMax function for multi-class classification in output layer and use optimization technique RMSprop to reduce the loss function.



MobileNet-v2, initially tailored for mobile and embedded applications, is chosen for its ability to strike a balance between accuracy and resource efficiency. This is particularly advantageous when dealing with scenarios characterized by constrained computational resources. Within the domain of multi-scale object detection, MobileNet-v2 generates a variety of feature maps with varying dimensions. These feature maps are subsequently fed into the SSD convolutional layer, which employs small convolutional filters to predict object scores and class offsets for predefined standard bounding boxes.

The MobileNet-SSDv2 architecture excels at extracting features from images and processing these features through SSD predictor layers. This

processing not only reduces image dimensions but also enables the recognition and classification of objects across a diverse spectrum of eleven classes. By harnessing the combined strengths of MobileNet-v2 and FPN, this architecture ensures memory-efficient and effective object detection, tailored to the specific task of identifying objects within these eleven defined classes. The MobileNet-SSDv2 detector significantly enhances the performance of the SSD detector, all while capitalizing on the memory efficiency inherent to MobileNet-v2 and the feature enhancement capabilities of FPN.

3.2.4 Pretrained model configuration:

The SSD MobileNet V2 FPNLite 320x320 download from TF Model will comes with pipeline.config file which has the information about the feature extractor, regularizer, number of Conv layers, batch normalization, data augmentation, batch size, activation function and optimizer etc. Are been provided based on the model trained with MS COCO dataset so we have updated some of these parameters are based on our requirement for better performance. I executed the provided Python code from the TensorFlow API to initiate the training process. Post-training, the API generated a checkpoint file in a specific format (typically .ckpt). This file serves as a binary repository encompassing all the model's weights, biases, and other essential variables, enabling subsequent inference and evaluation.

3.2.4 Inference:

After training the model, the next step is to deploy it for real-time predictions. To assess its accuracy, we use mean Average Precision (mAP). For efficient inference, we used an OpenCV library to implement a lightweight version of the model. The trained model is saved in a Protobuf (.pb) file, containing the graph definition and parameters in binary format. Additionally, a human-readable text graph representation is stored in .pbtxt format, vital for OpenCV operations.

Using the Video Capture function from OpenCV, we process input video from the local folder, making predictions and outlining object locations. To integrate this with Unity3D and OpenCV for augmented reality (AR) scenarios, we employ the Protobuf file by converting it into the ONNX model and configuration, enabling AR interactions based on the SSDMobileNet v2 Aircraft component detection.

C. Augmented Reality Implementations:

In this step, we focus on integrating the trained object detection model into an augmented reality (AR) environment using Unity 3D 2020.3.25f1 that could use Barracuda, MLAgents and AR Foundation and Unreal Engine 5.0 that could use Neural Network Inference plugin

3.3. Augmented Reality Implementations using Platforms e.g. Unity Engine, UE

3.3.1. Protobuf to Onnx Model conversion:

The ONNX model conversion involves transforming the deep learning model which is saved in the Protobuf (.pb) format into the ONNX format. ONNX (Open Neural Network Exchange) is an open-standard format that enables interoperability between different deep learning frameworks such as Caffe, PyTorch, CUDA, etc. Here's a brief overview of the ONNX model conversion process:

- Model (.pb): Start with the trained deep learning model saved in the Protobuf (.pb) format. This exported model from SSD MobileNet v2 contains the graph definition, trained parameters, and other essential components.
- ONNX Conversion Tool: Utilize an ONNX conversion tool or library compatible **tf2onnx** with our TensorFlow framework that provide tools for exporting .pb to .onnx format.
- Model (.onnx): The result is an ONNX model file with the extension .onnx e.g. savedmodel.onnx. This file encapsulates the same deep learning model but in a format that can be used across various platforms such as Unity Engine, Unreal Engine and frameworks, making it ideal for deployment and inference in Unity 3D environment and Unreal Engine 5.0.
- ONNX model Visualization: The custom trained model after converting into .onnx

format can be visualized through Netron which provides the information of the neural connection in the model with the weights, activation function, batch normalization, optimizer etc. the Fig. 4. and Fig. 5. shows the segment of the visualization.

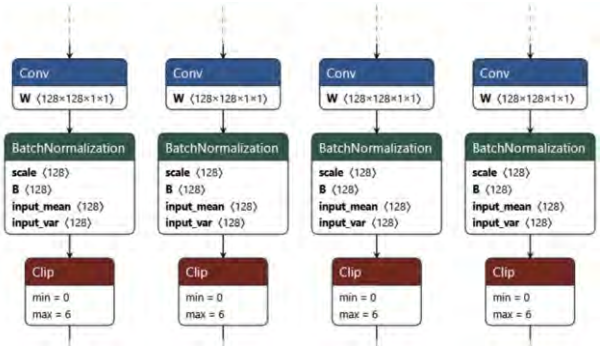


Fig. 4. Block visualization of ONNX model with convolutional layer, batch normalization and Activation function

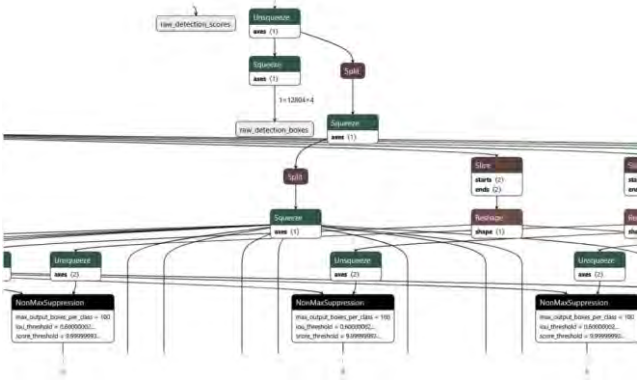


Fig. 5. Block visualization of detection layer and non-max suppression

3.3.2. Barracuda and AR Foundation

The integration of AR Foundation and the trained machine learning (ML) model in Unity for Android AR Camera involves combining AR capabilities with object detection and tracking using the ML model.

Barracuda: Barracuda is a neural network inference library developed particularly for ML models to work with Unity. It can import models in ONNX (Open Neural Network Exchange), an open-standard format that enables interoperability between different deep learning frameworks.

- AR Foundation Framework: Unity's AR Foundation framework is employed to create an augmented reality (AR) experience. AR Foundation is a versatile framework that enables developers to build AR applications compatible with both Android and iOS.
- Scene Setup: Within Unity, we set up a dedicated scene for our AR application with AR Session and AR Session Origin containing AR camera and necessary libraries. In this scene, we configure AR Foundation components, point cloud data, and plane detection as required for our specific AR scenario to display bounding boxes on the camera frame in the application development.
- Object Detection Model: The trained SSD MobileNet V2 model in ONNX format is imported into Unity. This model is responsible for identifying and tracking specific objects, such as aircraft components, within the AR camera's view by processing image frames.

3.3.3. Inference through platform (Unity)

Inference: We develop scripts in the Unity platform that compile to create an inference engine for the customized SSD MobileNet V2 object detection model. This engine processes the live video feed from the AR camera, runs object detection, and provides real-time object recognition results through the camera feed.

- Bounding Box and Overlays: Virtual objects and labels are annotated onto detected objects in the AR camera's view with real surroundings. This creates seamless integration of digital content with the real-world environment.

Implementing interactive Augmented Reality scenarios triggered by the detection and tracking of expected objects by the trained model. This can include displaying menus, additional information, animations, or other augmenting content associated with the recognized component. Targeting objects are detected, tracked, and augmented with virtual elements, enhancing user interaction and engagement in the augmented environment.

IV. MODEL EVALUATION

The model is trained to detect eleven aircraft components as targeting objects: Radome,

Cockpit, Drop tank, Vertical Fin, Missile, Air Intake, Airbrakes, Engine Nozzle, Aerial Refuelling probe, IRST. We employ generally used evaluation metrics such as mAP (Mean Average Precision) and recall by passing the test image to the trained model. Fig. 6 shows the results of object/component recognition.

A. Detected results

1) Intersection over Union (IoU): It measures the similarity and diversity between the predicted bounding box and the ground truth bounding

$$IoU = \frac{\text{Area of Overlap}}{\text{Area of Union}}$$

boxIt is important to define a threshold to define what is the correctness of the prediction for IoU.

$$\begin{aligned} T &\leftarrow \text{Threshold} \\ IoU \geq T &\rightarrow \text{Correct} \\ IoU < T &\rightarrow \text{Incorrect} \end{aligned}$$

2) Mean Average Precisiion (mAP): It is the area under the precision-recall curve. Mathematical Equation of mAP as follows.

$$mAP = \frac{\sum_{k=1}^{n} APi}{n}$$

Where AP_i is the average precision of class I, and n is the total number of classe

Fig. 6. Automatic aircraft component detection with bounding boxes

TABLE II. RESULTS OF MEAN AVERAGE PRECISION OF 0.50 TO 0.95 IOU SCORES OBTAINED

Evaluating Paramaters	IoU	mAP score
Average Precision	0.50:0.95	0.618
	0.50	0.831
	0.75	0.707
Average Recall	0.50:0.95	0.734

The results obtained can be further fine-tuned and improved for better performance of the model by implying these techniques:

a) Increasing the training dataset size: Bias would increase while Variance would decrease, improving the fit.
b) By altering the batch size: The model uses more samples, resulting in higher efficiency, stability, and scalability.
c) By increasing the epochs to optimal: Few epochs lead to underfitting of the data. Gradually increasing the number of epochs obtains maximum accuracy on the training set and reaches optimal performance.

ACKNOWLEDGMENT

This paper provides the object detection and aircraft component labeling. We will further extend the work by taking this as a foundational model for building real-time Augmented Reality Applications for model targeting and overlaying the 3D CAD model on physical aircraft, which improves interactivity and helps in addressing design issues and component maintenance.

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Opportunities with Generative AI to address challenges of Aviation Industry

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Abstract - Aerospace industry struggle with managing and utilizing many documents related to aircraft configuration, certification, operations, maintenance, and airworthiness. These documents are maintained, managed, and utilized for the entire duration of the aircraft life spanning across four decades. Many users and stakeholders search these documents regularly to find answers to meet design, certification, and airworthiness requirements. The existing search tools use simple keyword-based search not by semantics or meaning. Moreover, engineers need to go through these documents manually to assess the relevancy of the content for the specific context in question. This is very laborious and time consuming and highly domain intensive.

With the advent of technology advancements[1] in Artificial Intelligence (AI), more specifically the Generative AI (GenAI) techniques, there is a huge opportunity to address the challenges related with document search, comprehension, and summarization. This could be leveraged to augment an aerospace engineer knowledge to increase productivity while executing day-to-day engineering activities.

This paper elaborates the challenges associated with managing and accessing documents to get the relevant information, and then discusses the opportunities of leveraging GenAI and Knowledge Engineering techniques to address these challenges. The paper also provides a high-level view of the solution.

Keywords - Generative AI, Large Language Models [2], Aviation MRO, Document Search, Airworthiness Directives

I. INTRODUCTION

The aerospace industry produces huge volumes of data; Figure 1 captures a list of the kinds of documents produced in different stages of its life cycle. Managing and searching for this data is an important activity. Any productivity improvements in this process lead to huge benefits.

Aircraft maintenance involves review and analysis of various documents, historical maintenance records, airworthiness directives, operation manuals and other such information. Safety is paramount in aircraft industry. European Union Aviation Safety Agency (EASA) [9] and Federal Aviation Administration (FAA) [10] issue Airworthiness Directives (AD) that must be complied for continued airworthiness of the aircraft by everyone including aircraft manufacturers, operators, and maintenance bodies. Non-compliance leads to grounding of the aircraft. With aircraft in operation for more than 40 years, managing the historical documents and their analysis is a challenging and time-consuming process.

When a new problem shows up, engineers search the document repository to find the right set of documents. They write an analysis report by reviewing the documents. With the existing keyword-based search systems hosted by regulators, it takes an engineer at least a few days to complete this task. Today, this manual process takes significant effort considering that more than 25,000 aircrafts are operated across the globe.

Building a Question Answering system to improve the search experience for all the stakeholders involved improves the productivity by at least 50%

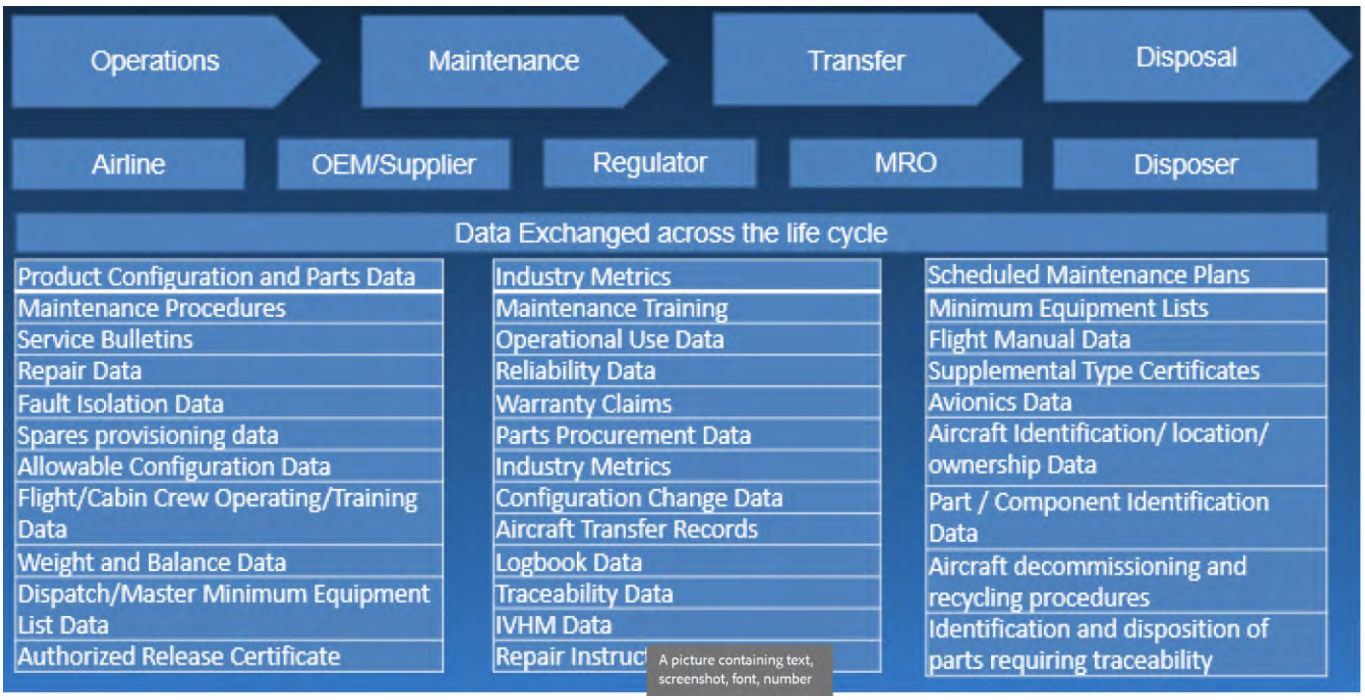

Figure 1: Stakeholders and Data Exchanged across Aircraft Lifecycle

which in turn helps in reducing Aircraft-On-Ground (AOG). This is an important metric in Aircraft Industry.

This paper discusses the opportunities to address each of these challenges by leveraging various AI techniques. It provides a high-level solution architecture illustrating its various technology components. It also presents various evaluation [4] metrics and approaches. The paper con-cludes with a summary of outcomes till now and way forward.

2. MOTIVATION FOR THE CURRENT WORK

The search system supported by aviation regulatory agencies are rudimentary. They are mostly built on keyword-based search techniques. This is time consuming, and the user is expected to know what keywords to enter to find the relevant documents for a particular problem. Some of the common challenges in the search process are:

1. Ensuring availability and accessibility of most recent and up to date information coming from multiple sources.
2. Variations in the terminology used for similar content across various documents and sources.
3. Searching and identifying most relevant and applicable content from a huge volume of documents with various filter conditions.

The search systems provide the user with a list of documents that the user is expected to go through one at a time to find the information that the user is after. Identifying required documents to analyze a particular problem and arriving at a solution takes considerable amount of time. In addition, users are expected to know the exact keywords to search for which is challenging for inexperienced users.

A Question Answering solution has been envisaged and is being piloted considering a subset of the documents in aerospace domain. The solution is planned to be built on the publicly available Airworthiness Directives (AD) documents hosted on the European Aviation Safety Agency (EASA) and Federal Aviation Administration (FAA) portals. Next section provides a high-level view of the solution.

3. PROPOSED SOLUTION

3.1. Solution Considerations

At the broad level, key solution requirement is to have a question answering system with the capability to provide right answers to the

questions posed by the engineers. The system should be able to search the most relevant document and specific relevant sections of the document for the answers to the input question.

In the context of the current scope of the solution involving Airworthiness directives, key consideration is to augment engineers in the Airworthiness Compliance Analysis, Resolution and Reporting. Accordingly, the following are the two broad level requirements considered.

- To find the most relevant ADs given a criterion (make, problem description, time pe-riod)
- To generate answers to the questions on the contents of Airworthiness Directives.

Following are some of the aspects considered in the design of the solution:

- Accuracy and relevancy of the answers
- Context Relevancy
- Faithfulness and traceability to the original source of information
- Ability to reduce the hallucination.

By leveraging a combination of technologies such as GenAI, LLMs[6], Knowledge Engineering Techniques [4] and Frameworks[5], and domain specific ontologies / knowledge graphs, it is possible to address these challenges taking into account the above considerations.

3.2. Solution Overview

The developed system is open question answering system powered by LLMs that can answer questions from the MRO Engineers. A typical question can be "Given a new maintenance problem, what are the most relevant historical AD documents that are applicable?". The system will also act as a co-pilot in writing an analysis report for a maintenance request; this involves detailed analysis of many AD documents and summarization of information.

The search solution can be built like a typical enterprise search that retrieves documents for a search query using relevance calculated via heuristics. It will be a purely information retrieval exercise. On the other hand, one can also use Generative AI models such as GPT to answer user questions directly. It may still produce very good results in many cases but may not be very reliable and will lack context. This paper presents how providing the right documents to LLMs (Retrieval Augmentation) to produce the answers helps in improving accuracy, reliability of the system.

4. SOLUTION APPROACH AND ARCHITECTURE

4.1. Solution Approach

Question Answering (QA) systems powered by Language Models (LM) directly respond to user's questions either by generating the answers or by extracting it from the source documents. On the other hand, search systems only list the documents which the user must browse through to find the information. Naturally, QA systems are more interactive and help in making faster decisions and to perform detailed analysis by asking follow-up questions.

In this work, techniques involved in building a QA system specifically on AD documents are explored. It is focused on the following four aspects.

1. A flat text representation doesn't do justice to the AD documents; Hence Knowledge Graphs (KG) are used to store the relationships in the data. This helps in answering questions like "What are the most frequent issues in A380 aircraft landing gear?" which requires 'A380' ADs specifically on 'landing gear' component.
2. To answer any question correctly, it is important to understand the intent and meaning well. By leveraging language models, the current work comprehends the question and creates a strategy to answer it.
3. The LLMs have gained a lot of world knowledge because of pre-training and can an-swer any question very competently. However, aircraft engineers want specific an-swers from the AD documents only. The solution is to send a set of shortlisted docu-ments to LLM from which it can generate an answer. This technique is known as Re-trieval Augmented Generation (RAG). This also alleviates LLM's tendency to halluci-nate.
4. Finally, it is important to objectively evaluate the QA system with metrics that capture

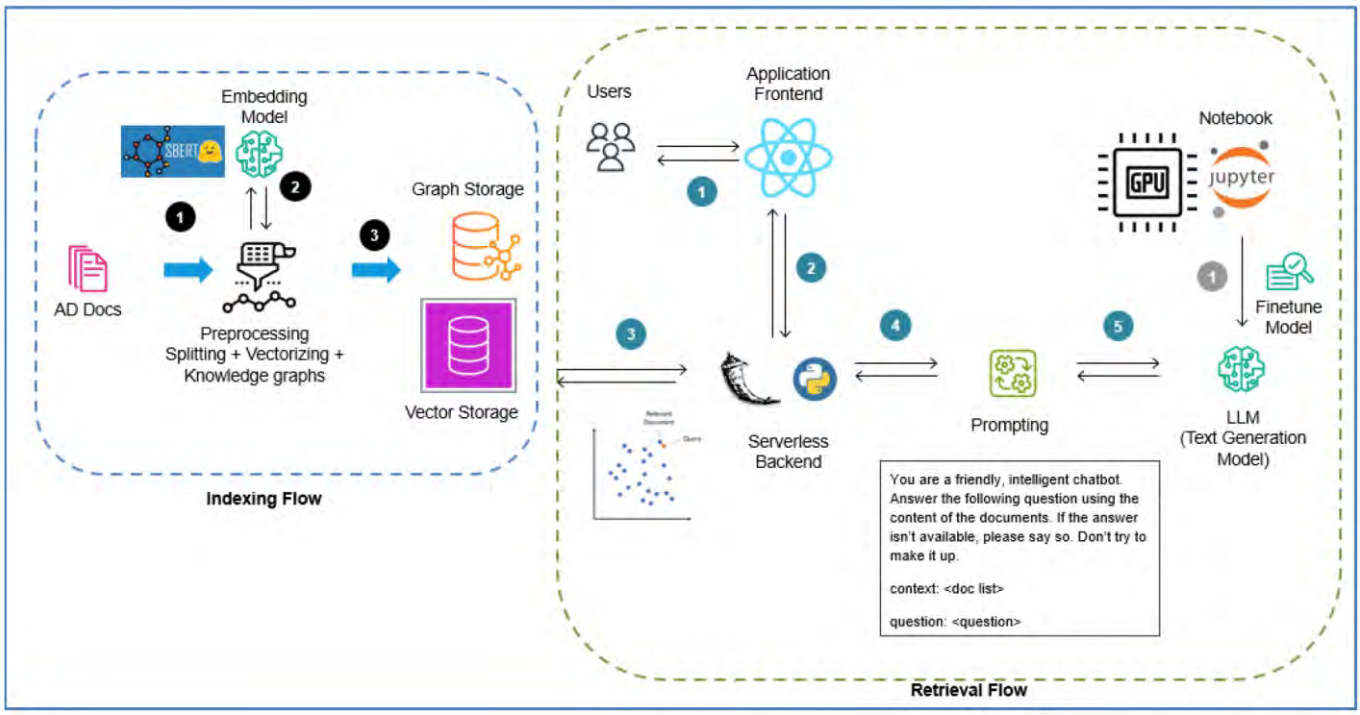

Figure 2: Solution Architecture

relevancy, faithfulness, and reliability. This is critical for the success of any production system especially in aircraft industry that involves safety and regulatory compliance.

In a QA system, users are free to ask any type of open questions. The questions can be simple factoid, descriptive or even that requires step-by-step thinking. Some typical questions from engineers are,

- What are the corrective actions to be taken as per the latest ADs for wing upper cover issues in A380 aircrafts?
- What are the latest guidelines for overheat detection system issues in A350 aircrafts?

Answering them involves understanding the question, finding the AD documents that contains the answers and finally generating an answer.

4.2. Solution Architecture

Building a Retrieval Augmented solution for QA involves two stages. Indexing and Retrieval as shown in Figure 2.

Indexing: The AD documents are preprocessed, vectorized and stored in a vector store and knowledge graph store. Better preprocessing, choice of models for vectorization are important considerations for building a highly accurate system.

Retrieval and Generation: When a user asks a question, the most important documents from the Vector & Knowledge Graph store are retrieved. The documents are bundled into prompts and passed to LLMs. The generated answer from LLMs is postprocessed and returned to the user.

4.2.1. Indexing Flow

Following are the various steps in involved in Indexing Flow.

Preprocessing [8]: The AD Documents contain information about the aircraft problems, their resolutions, reasons and compliance data for various make and models. This data is hierarchical in nature and hence stored in a knowledge graph format. KGs have high information density which helps to pack lot of information in relatively fewer tokens. This is an advantage when using LLMs with smaller context length.

As Language models can't attend to text beyond its context length, the documents are split into smaller chunks. For every chunk, metadata is added and a document summary that helps in maintaining document context which otherwise is lost in chunking process.

The above are a few examples of specific preprocessing that are followed for AD documents. However, every dataset is different, it is recommended to spend good chunk of time to under-stand the data deeply which helps in devising optimal preprocessing method.

Vectorizing: Every chunk in the document is vectorized using a Language Model. It is important for semantically similar AD documents to be closer in vector space as well by some distance metric (For example, cosine distance). Open-source models specifically trained for semantic search such as sentence-transformers [5] are used during initial experiments. For pro-duction, LLMs can be used to create the embeddings.

Finetuning the embedding model on AD documents is a great lever to improve the quality of the QA system.

In general, lot of care must be taken in building out the indexing flow as the quality of the retrieval depends on it. It is recommended to evaluate the indexing flow separately.

4.2.2. Retrieval and Generation Flow

Following are the various steps in involved in Retrieval Flow.

Relevant Documents Retrieval: This is another vital task in the RAG pipeline as the quality of answers produced by LLMs depend directly on the documents that are passed to it. If the documents don't have the answer to the question, LLMs will fail to answer the question.

For the vector storage, the top-k retrieval is based on Nearest neighbor or cosine distance in the vector space between the query text and the AD document chunk.

Considering that an LLM with 8k token context length is used for answer generation, the hyperparameter 'k' is set as five assuming the chunk size is ~ 1k tokens. During planning, the size of prompting text, conversation history and question should be considered when deciding this parameter.

For the KG index, the retrieval uses a graph query language such as GraphQL, Cypher and others. Again, with few-shot prompting, LLMs are used to generate the queries that retrieves the data from the Knowledge Graphs.

Answer Generation: Once the shortlisted KG documents that contain the answer for a particular question are available, it is bundled with a prompt that contains the question, the retrieved documents along with instructions to the model. Model is instructed to generate the results only from the documents passed to it. In addition to the final answer, the user is provided with references to the documents. If the user wishes to review the material to get more information, the references will be helpful.

5. RESULTS AND DISCUSSIONS

The answers produced by the QA system should be evaluated for accuracy and reliability. As LLMs also have to the potential to make things up, it is essential to evaluate the system for performance. As LLMs write their answers in their own language, there is no easy way to compare them with ground truth answers which are written by human annotators. A word-to- word comparison is out of question.

Eyeballing the answers from LLMs is a good enough technique when starting the application development. As things mature, it is recommended to create an evaluation dataset and measure the quality of the answers.

5.1. Creating the Evaluation Dataset

To evaluate the system, an evaluation dataset (question, ground truth answers and context documents) is created by human annotators. The questions in the dataset have varied levels of

complexity; simple questions have direct answers from the documents. Complex questions re-quire referring to multiple documents and summarize to generate the answers from them. A few sample questions from the evaluation dataset are shown in the Appendix.

5.2. Evaluation Metrics

As the QA system is built on RAG design pattern, the following evaluation metrics better cap-ture the reliability.

Faithfulness: This metric represents if the generated answer is consistent with the documents passed to the LLM. Any information outside of the context documents is discouraged.
Context Relevancy: This captures the quality of the retrieved documents from the data store for a given question.

Answer Relevancy: This represents how good the generated answer is to a given question.

Answer Similarity: This captures how close the generated answer is to the ground truth an-swers in the semantic vector space.

Harmfulness: It measures if there is any malicious content in the generated answer.

5.3. POC Results

The POC (Proof of Concept) is built on a simple pipeline on the EASA documents.

We have considered two approaches.

Approach 1 uses Knowledge Graph for storage. Document Retrieval is implemented using graph queries and BERT based embeddings.
Approach 2 uses vector database for storage and semantic search for retrieval.

The below results are with hyperparameters: top k = 4, temperature = 0 on an evaluation dataset of 10 questions. The scores range from 0 to 1 with 1 being the perfect score.

Metric	Approach 1	Approach 2
Faithfulness	0.76	0.69
Context Relevancy	0.65	0.57
Answer Relevancy	0.85	0.80
Harmfulness	0.00	0.00

5.4. Discussion on results:

Both Approach 1 and Approach 2 results are very comparable from the basic pipeline. However, the KG approach will be able to answer advanced queries that involve relationships in the documents.

The following parts of the pipeline will be optimized for further improvements in the system.

- Preprocessing of the AD documents (Creative use of document summary, metadata in chunking process)
- Choice of models for embedding creation
- Choice of retrieval techniques from document storage (keyword, embedding & hybrid)
- Choice of LLMs (Different types of LLMs such as Cohere, OpenAI, Anthropic, Llama [7])
- Choice of LLM hyperparameters
- LLM model finetuning [6]
- Advanced Query planning techniques such as Agents [3]

Building a production grade application requires a lot of care and experimentation as this in-dustry is safety critical. Multiple experiments will be conducted, and the performance is meas-ured to decide on the optimal choices. Without this formal evaluation framework, it is impos-sible to measure the system during testing and in production.

6. CONCLUSIONS

LLMs have excellent language understanding and impressive reasoning abilities. This is a transformative technology using which one can reimagine many NLP applications including search, recommendation systems and others. This paper explains how aviation knowledge search can be reimagined like a conversational QA system and discusses various techniques to build one.

Aircraft Industry spends about 15-30% in maintenance cost. By providing the ability to find answers to the questions quickly, this solution enables engineers to make decisions and write reports faster thus reducing the maintenance cost.

This is a horizontal solution that can be applied across verticals such as manufacturing, automotive, financial services for regulations and compliance, troubleshooting and maintenance and various other use cases.

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10. FAA Federal Aviation Administration - https://www.faa.gov/

APPENDIX

Question	Ground Truth Answer	Context
Summarize all the Flight Control issues faced by A320 aircrafts	A320 aircrafts face different types of Flight control issues like Trimmable Horizontal Stabilizer actuator issues, Angle of Attack (AoA) probe blockages, Electrical System failures etc. Angle of Attack (AoA) probes is very important for an aircraft stability and these probes are to be monitored carefully. The AoA probes should not be blocked which will affect the safe flight and hence for the safety of the aircraft these probes are to be monitored by ELAC. Upgrading ELAC units with latest ELAC L99 is recommended in A320 aircraft to ensure the safe flight of the aircraft	<Top K Relevant documents from AD documents for A320 models>
What is the corrective action for Fuselage issues in Airbus models	Aircraft Fuselage will generally have common issues that needs to be inspected and corrected. Airbus aircrafts also face some issues in locations in fuselage like Type A Emergency exit door frames, Fuselage Bulk Cargo Door Frames, Structure Frames and Joints etc. These issues are to be inspected for cracks and corrected then and there to avoid structural integrity issue in an aircraft. These unsafe conditions should be addressed using Service bulletins (SB) issued by Airbus like SB A340-53-4027	<Top K Relevant documents from AD documents for Airbus family>

Test-Time Augmentation for Improving the Accuracy of Deep Learning based Defect Inspection Models

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Abstract - The effectiveness of Deep Learning (DL) based computer vision models has exponentially improved over the past decade with the development of complex neural network architectures. Even such complex models trained under ideal conditions tend to exhibit a degradation in accuracy when applied to challenging real-world scenarios, such as industrial asset inspection where data insufficiency is an additional challenge. The seemingly simple process of Test-Time Augmentation (TTA) provides a boost in accuracy. This study presents an approach for applying TTA to defect inspection problems while analysing the impact made by the various parameters within the TTA process. The aim of this work is to frame the best practices and design considerations towards maximizing the effectiveness of TTA in an Artificial Intelligence (AI) system applied to asset inspection. The proposed recommendations are discussed, and their effectiveness is studied through experiments on asset inspection datasets.

Keywords - Asset Inspection, Test-Time Augmentation, Defect Inspection, Deep Learning, Computer Vision

I. INTRODUCTION

Development, training, and deployment of DL models for vision tasks has made great strides in the past few years. Industries have been increasingly adopting these models for the purpose of asset defect inspection. Once the models have been deployed for actual use, every incorrect prediction could negatively impact the business process, especially in a sensitive task like inspection where false negatives could impair the timely identification of defects. This has driven the need to maximize model accuracy in production. A routine process that partly alleviates the problem is data augmentation [1] done at the time of training the model, which involves performing a series of transformations on the set of training images. A different approach which also leverages data augmentation is Test-Time Augmentation (TTA) [2], wherein the data augmentation is done on the test dataset to obtain multiple variants of each test image. The trained Deep Learning model makes predictions for each variant individually and these predictions are aggregated into a single result. TTA introduces a robustness to the system which improves the model's accuracy.

The benefits of TTA have been established through previous literature, but it is often overlooked or applied without a thorough assessment of the breadth of augmentation possibilities. Choice of augmentation possibilities, as seemingly simple they may be, do have an impact on the model predictions, potentially degrading system accuracy. This paper presents an approach to applying TTA to defect inspection problems while analysing the impact made by critical aspects within the TTA process such as the number of variant images, configuration of composite image transformation pipelines and the choice of result aggregation algorithms. This work highlights the

differences in strategy and parameter selection depending on the downstream task – image classification, object detection or segmentation – and corroborates the principles laid out through experiments and analysis of the results on asset inspection image data.

This paper also explores the nuances of the TTA system and assists in navigating the various trade-offs of the design choices such as favouring precision over recall and contrasting the gain in accuracy while incurring additional compute cost. Finally, this work aims to frame the best practices, parameters, and design considerations to maximize the effectiveness of TTA in an AI (Artificial Intelligence) system.

II. TTA – APPLICATION & EVALUATION

During the ML model training phase, standard data augmentation is a routine activity. This process is a staple for anyone grappling with insufficient or imbalanced volumes of data. The standard data augmentation, as depicted in Figure 1, is performed by applying transformations such as flips, crops, pixel shifting and contrast changes to the training images. The set of augmented images along with the original set of real images is used for training the ML model. The artifact generated from this entire exercise is the Trained AI Model.

Figure 1. Typical model training process using data augmentation.

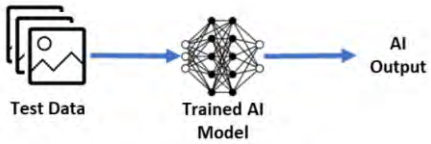


Figure 2. Typical AI model inference process

A. Applying TTA to an ML Model

TTA is achieved by performing a set of augmentations on the test image and then aggregating the results over all the images to arrive at the final output. The standard inference process simply requires the test images to be directly passed to the Trained AI Model as input. For a classifier model, the model response is a set of probabilities assigned to each possible class respectively. The class with the highest probability is designated as the final output of the model, as depicted in Figure 2.

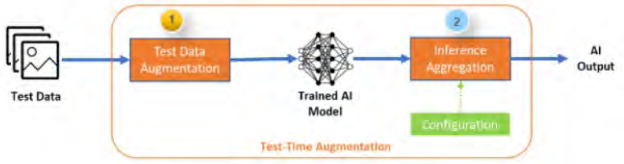


Figure 3. AI model inference process with Test-Time Augmentation

The proposed TTA operations in this paper are a part of the inference process. The entire mechanism can be separated into two logical parts as depicted in Figure 3:

1) **Augmentation Transforms:** This process is similar to the training time augmentation; several transform operations are performed on the incoming test images. Consequently, the test set volume is now multiplied. All the images are then forwarded to the AI model for generating the output.
2) **Result Aggregation:** The second part of the process kicks in after the AI Model has generated responses for all the augmented versions of an image. This submodule is responsible for aggregating the results across all the versions of a single input image and calculating the final unified output. The configuration parameters passed to the aggregation process can significantly alter the output and offer a finer level of control, especially in terms of balancing the precision and recall of the model.

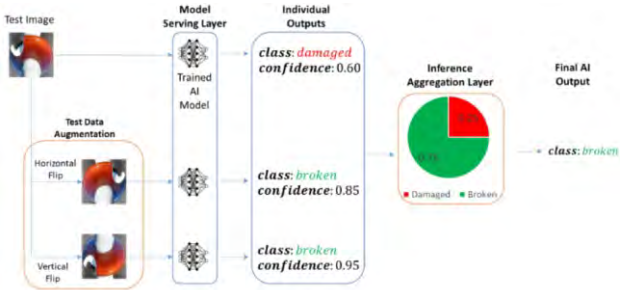


Figure 4. Concrete example of Test-Time Augmentation process

The core principle of TTA is to test the model against a slightly shifted distribution of images and build a consensus by having the model infer on all the image inputs [2], as depicted in Figure 4. While the model may produce incorrect results on some of the images (including the original test image), the aggregated consensus is more likely to be accurate as compared to a single image inference (correction). As seen in the concrete example above, the output on the original image was incorrect, yet the final TTA output is correct since it built a consensus over three images (original + two augmented variants). The inference on augmented images makes the test time process robust to small artifacts and features which might lead the model to make an incorrect prediction.

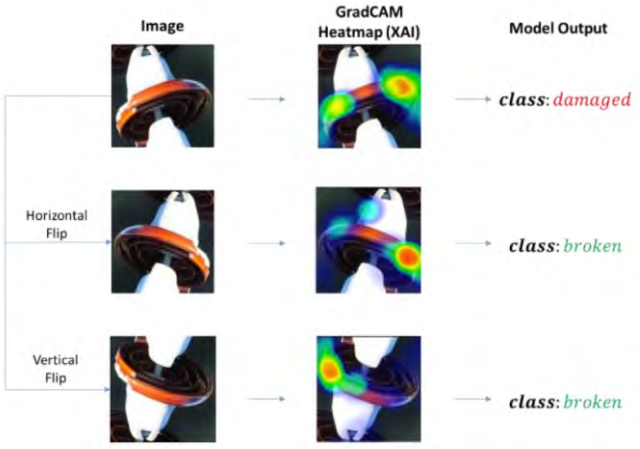


Figure 5. XAI Visualization on Augmented Images

A similar example is analysed in Figure 5 using Explainable AI (XAI). The gradcam heatmap layered on top of the respective images highlights which features of the image contributed the most to the final decision of the model. This goes to show that in the original test image, the model prediction was influenced by features outside of the 'broken' area, leading to an incorrect prediction. In contrast to that, the model predictions on the augmented image rely heavily on the actual 'broken' part of the insulator and thus give an accurate prediction.

B. Assessing TTA-induced Accuracy

TTA is a multi-layered process with many nuances. It should not be assumed that TTA will enable a flat boost in accuracy. The results post TTA-processing should be analysed carefully to understand the trade-offs and to further tweak the TTA pipeline. This section describes the methodology to assess and interpret the impact of introducing TTA into an ML pipeline.

1) Classification Models: The TTA module may give a final output which is incorrect whereas the output on the original test image was correct, a Corruption. The reversed scenario is termed as a Correction. See Table 1 for details. Since the TTA module applies the trained model in a shifted hyperspace, there are bound to be Corruptions even while using an ML model that is performing well. The difference between these Corrections and Corruptions is the actual gain in accuracy as induced by TTA.

TABLE 1
TTA EVALUATION OF CLASSIFICATION MODELS

Test Images	Single-Image Testing Result	TTA Module Result	Evaluation
01	Correct	Incorrect	Corruption
02	Incorrect	Correct	Corruption
03	Correct	Correct	Unchanged
04	Incorrection	Incorrect	Unchanged

The accuracy on the test set would suffice to compare the standard inference process against the TTA module inference. However, only a deeper look at the corruption and correction counts gives a true picture of TTA-induced changes as both of them could cancel each other out.

2) Object Detection (OD) Models: The standard inference process for OD models generates a set of bounding boxes along with a class ID and confidence score associated with each box. OD models are evaluated by their Precision and Recall scores which are often clubbed into a single metric – the f1 score. Unlike classification, it is not possible to simply aggregate single results. The TTA module applied to input images induces flips or shifts in the co-ordinate system and accordingly the bounding boxes generated on these images are also unaligned with the original input image. The TTA module must project all the boxes back to the

original input image and then execute an aggregation strategy to combine multiple bounding boxes. The standard strategies involve either Non-Max Suppression (NMS) or Weighted-Box Fusion (WBF) [3]. These strategies always result in an increase in the number of bounding boxes predicted, thereby boosting the Recall of the final results while potentially reducing the Precision.

Therefore, a comparison of f1 scores is not viable here and it is necessary to examine the Precision and Recall scores individually to assess the benefits of applying the TTA module to an OD model.

3) Segmentation Models: The output of these models is similar to that of OD models but more granular. The detected object is indicated by a polygon boundary instead of a bounding box as the model assigns an object class or the background class to every pixel in the image. The assessment is also akin to that of OD models, expressed in terms of Precision, Recall and f1 but can also be expressed in terms of IoU.

III. TTA CONSIDERATIONS

This section describes the critical implementation factors which make-up the TTA module. Each of these is a design choice which influences the efficiency and effectiveness of the TTA module. Building an inference system with TTA is an iterative process that involves evaluation of the module's output, interpretation of the results and subsequent modification of the TTA module through the various considerations described in this section.

A. Number of Augmented Variants

As the goal is to build a consensus by inferencing on multiple images, the natural implication is that larger the number of augmented images, the more reliable is the consensus and hence, the TTA output. While this is true, there are several practical hindrances which need to be addressed. Every additional augmented image will require additional time and compute for the AI model inference process. The process is depicted in Figure 6.

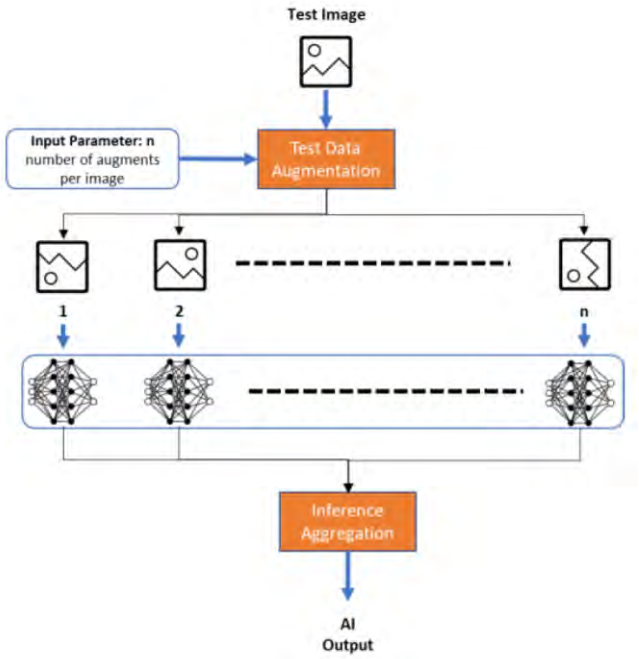
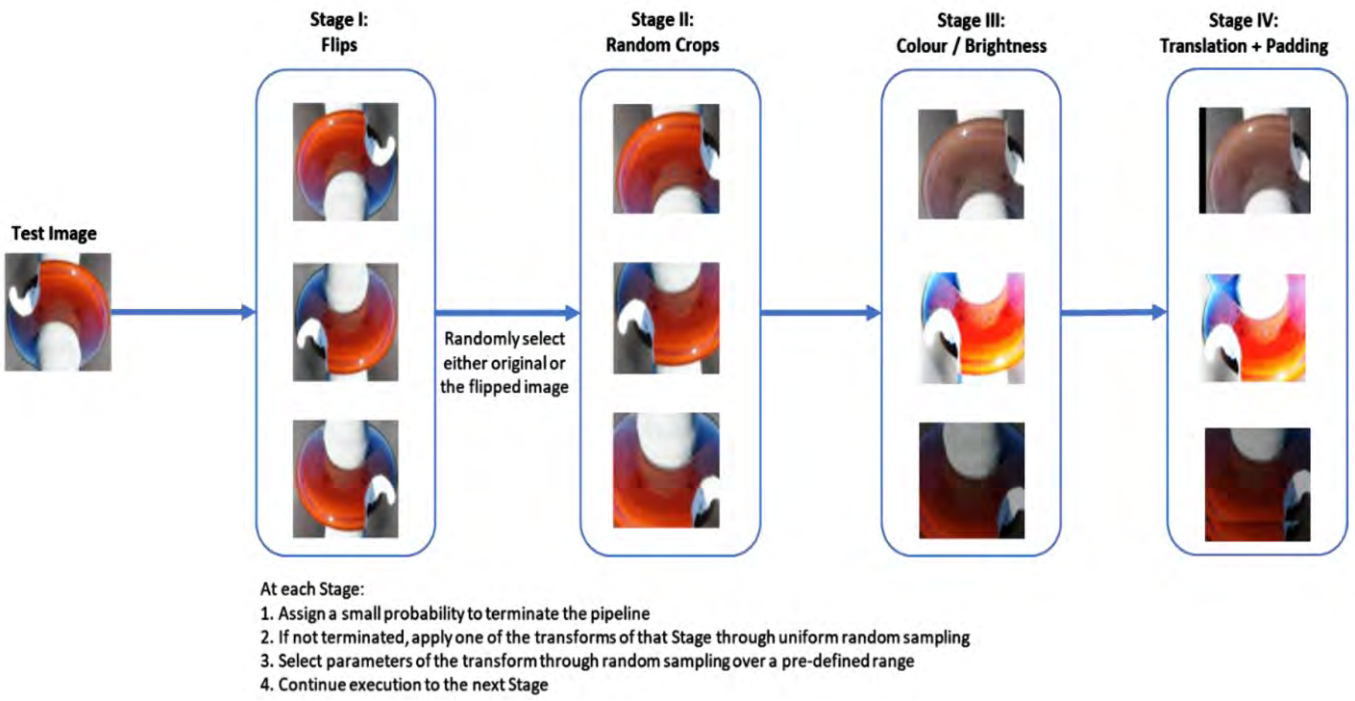


Figure 6. Model inference being aggregated over all n augmentations of a single test image.

B. Multi-Stage Pipeline Design

The central tenet of the image transformation pipeline design is to break it down into multiple stages with a certain probability of the workflow terminating prior to reaching the respective stages. This allows the system to generate a very high number of augmented variations with a handful of transforms. Another important consideration is to keep the simpler transforms (such as flips) in the earlier stages as they are simple to perform and quite proven to be effective at TTA. Figure 7 depicts a four-stage pipeline capable of generating a wide variety of composed transform operations. Such a pipeline is flexible and can be easily parametrized to generate a given number of augmented variations. Further, by controlling the stage transition probabilities, one has a fair amount of control over the type of augmentations we would prefer to generate while allowing room for variations to be included.

The final aspect of the TTA pipeline, this part brings together the output from all augmented images into a single decision. The example in Figure 4 utilizes a weighted-voting strategy where the confidence scores of individual model predictions are used as weights. An alternative strategy for



7.Multi-stage Image Transformation Pipeline

classification models is to use a simplified voting strategy which disregards the confidence scores entirely. Both strategies are effective while the former allows for advanced decision-making and analytics. It should also be noted that weighted voting is more effective when the number of augmented images is high.

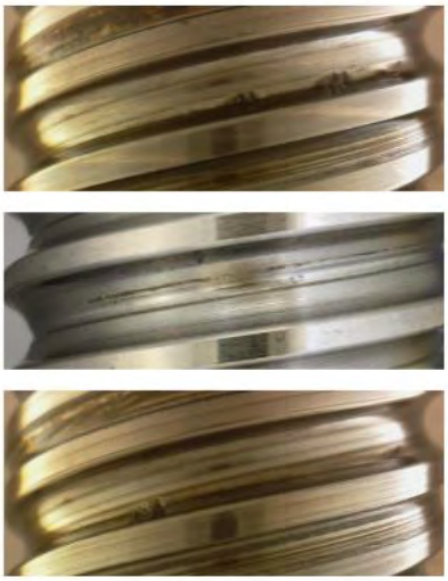


Figure 8. Samples images from the Ball Screw Dataset

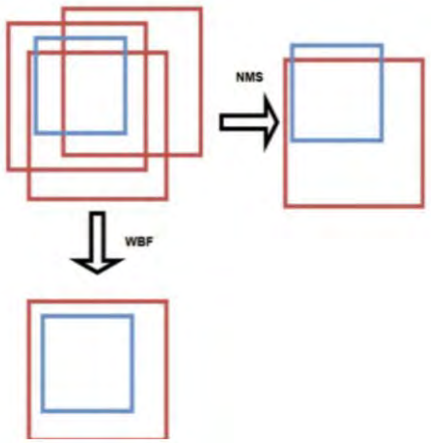


Figure 9 . Difference in the aggregation methods of NMS and WBF. Red boxes are the model predictions, and th e blue boxes indicate the actual object (Ground Truth)

For OD models, NMS (non-max suppression) and WBF (weighted-box fusion) algorithms can be used for aggregation. These algorithms are used to aggregate the predictions on a single image. When employing TTA, the bounding box predictions on the augmented images are projected (transformed) back to the original test image, following which the above aggregation

strategies can be directly applied. The difference between both approaches is depicted in Figure 9. Whereas WBF converges to a new bounding box by averaging all the candidate box co-ordinates, NMS eliminates the unlikely candidates through the use of confidence scores and overlaps with other boxes to retain a single candidate box as the final output.

While Segmentation models have output that is more closely associated with OD models, the aggregation strategies are adapted from the Classification models. As each augmented variant has a class prediction for every pixel, the standard approach is to aggregate all the classes for a pixel and choose the common class based on consensus. Additionally, the confidence score can be used for weighted voting during aggregation.

IV. EXPERIMENTS & RESULTS

Figure 10. Sample images from the Modified Insulator Dataset

As part of this study, multiple experiments were conducted on asset inspection datasets. DL models (classification [4] and OD [5], as applicable) were trained and evaluated to establish a baseline. Following that, the TTA modules were integrated into the respective inference pipelines and evaluated against the baseline. Within each experiment, different Configuration parameters were evaluated within the Aggregation process. In this work, three datasets have been used:

1) Insulator Dataset (Modified): A modified version of the insulator dataset [6], it has two defect classes and a third Defect-Free class. Sample images for each class are shown in Figure 10.

2) Ball Screw Dataset: An OD and Segmentation dataset [7] used for industrial wear detection; it shows surface damage on the assets. Sample images are shown in Figure 8.

3) Component Body Parts Dataset: Privately collected OD dataset of various assets with multiple components.

A. Classification model on the Insulator Dataset

Through the experiment depicted in FIGURE 11, it can be observed that compared to the accuracy at Number of Augmentations=0 (no TTA), even a small number of augmentation operations results in a 5-8% gain in accuracy. While the highest accuracy for this set of operations is observed at n=10 (red box), the relative gain is not significantly higher than n=4 (blue cross). Depending on business context, it may be prudent to bear additional costs and compute to squeeze out the maximum accuracy, but our experiments indicate that even a small number of augmentations in the range [n=2, n=4] is sufficient to draw out most of the benefits of TTA without incurring a heavy time and cost penalty.

TABLE 2
MULTI-STAGE AUGMENTATION SETS USED IN THE CLASSIFICATION EXPERIMENTS

	Stage 1	Stage 2	Stage 3	Stage 4
Aug. Set 1	Random Flips	Random Crop		
Aug. Set 2	Random Flips	Random Crop	Brightness	Translation
Aug. Set 3	Random Flips			
Aug. Set 4	Random Flips	Random Rotation (90, 180)		

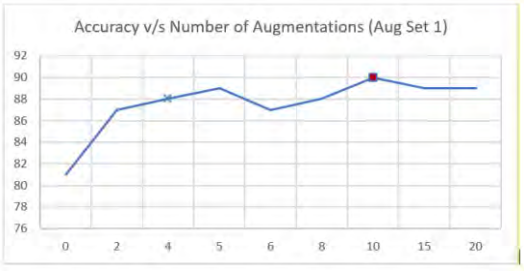


Figure 11. Accuracy calculated with TTA varying the number of augmented variants.

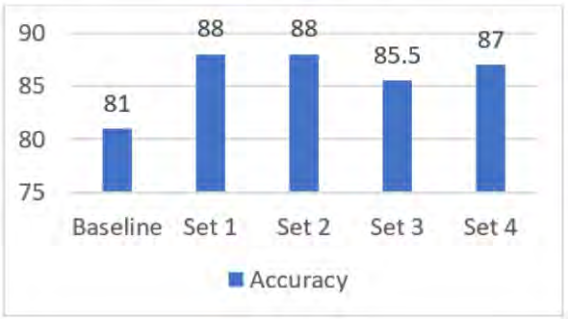


Figure 12. Accuracy on the Insulator Dataset with different sets of Augmentation Operations

The aim of the next experiment is to compare single stage augmentation pipelines with more complex multi-stage pipelines. The results, as depicted in Figure 12 are context dependent and would tend to vary with the complexity of the underlying datasets. For the insulator dataset, it is observed that very complex pipelines (4 stages) are not any more effective than a two-stage pipeline. It should also be noted that a single-stage pipeline was unable to induce sufficient variation in the images and has the lowest accuracy of the TTA variants.

B. OD model on the Ball Screw Dataset

As discussed in the previous section, the OD model's TTA module is assessed using the Precision and Recall scores. For the scope of this study, this experiment compares the effectiveness of both aggregation strategies (NMS and WBF). Further, previous experiments have indicated that simpler transformations such as flips are effective. To delve a level deeper into this aspect, the experiment also compares the effectiveness of horizontal and vertical flips against the inclusion of diagonal flips.

It is observed that through the TTA module with NMS aggregation, the Recall is increased by five points without compromising the Precision. This is a significant gain in accuracy achieved at test-time without any model retraining or enhancement. Furthermore, for both aggregation strategies, the inclusion of diagonal flips has resulted in a slight dip in accuracy though it is by a small margin. This is in-line with the Classification experiments wherein it is observed that for most use-cases, it is appropriate to start with a simple augmentation pipeline and integrate complex transformations if the simpler pipeline is not effective.

TABLE 3
COMPARISON OF TTA AGGREGATION STRATEGIES WITH OD MODEL ON THE BALL SCREW DATASET

Inference Pipeline	Augmentation Operations	Aggregation Strategy	Precision	Recall
Baseline	N/A	N/A	0.64	0.54
TTA	Flips – Horizontal, Vertical	NMS	0.64	0.59
TTA	Flips – Horizontal, Vertical, Diagonal	NMS	0.59	0.58
TTA	Flips – Horizontal, Vertical	WBF	0.60	0.56
TTA	Flips – Horizontal, Vertical, Diagonal	WBF	0.57	0.56

C. OD model on the Component Body Parts Dataset

For the Component Body Parts dataset, this study explores the utility of TTA as a control function with respect to Precision and Recall. Business requirements drive the decision on whether a model should favour Precision or Recall. In the case of OD models, the confidence score and IOU threshold are two aspects which can be controlled to balance Precision and Recall. The aim of this experiment is to ascertain the effectiveness of TTA as a third control parameter. Asset defect inspection often requires that the model maximize the Recall as the intent of the system is to alert on the presence of defects or damage, even at the cost of slightly increasing False Positives.

The results in Table 4 depict the Precision and Recall trade-off with various configurations involving the use of TTA and reduction of the confidence threshold from 0.75 to 0.5. As is generally expected, lowering the threshold leads to an increase in Recall at the cost of Precision. However, the drop in Precision is noticeably severe.

TABLE 4
PRECISION & RECALL ANALYSIS BY VARYING THE CONFIDENCE SCORE ON RESULTS OBTAINED USING TTA ON THE COMPONENT BODY PARTS DATASET

Operation	Conf. Score	Precision	Recall	Delta Precision	Delta Recall
Baseline	0.75	0.577	0.905	N/A	N/A
Reduce Confidence Threshold	0.5	0.492	0.938	-0.085	+0.033
Reduce Confidence Threshold + TTA	0.5	0.459	0.944	-0.118	+0.039

The application of TTA provides an extra control mechanism where the Precision loss is better restricted considering the improvement in Recall. To be precise, the TTA output has a Precision loss of 1.65 per 1 point of Recall gained. While simply reducing the confidence threshold has a loss of 2.57 per 1 point of Recall gained, indicating that the TTA option is more effective. On the other end of the spectrum, Applying TTA to the reduced confidence threshold leads to the largest drop in Precision but also nets the biggest Recall again, thus providing another option where maximizing the Recall is critical.

D. Segmentation model on the Ball Screw Dataset

TABLE 5
PRECISION & RECALL ANALYSIS BY VARYING THE IOU THRESHOLD ON RESULTS OBTAINED USING TTA ON THE COMPONENT BODY PARTS DATASET

Operation	IOU Score	Precision	Recall	Delta Precision	Delta Recall
Baseline	0.75	0.577	0.905	N/A	N/A
TTA	0.5	0.544	0.925	-0.033	+0.020
Reduce IOU Threshold	0.3	0.544	0.972	-0.033	+0.067
Reduce IOU Threshold + TTA	0.3	0.512	0.982	-0.065	+0.077

In the second part of this experiment, the influence of reducing the IOU score threshold is studied. The results are tabulated in Table 5. IOU threshold reduction is a relatively more drastic control measure. In this case, it is observed that the Recall is greatly improved and while Precision is lost, it is not as sharp a drop as in the earlier case of confidence score thresholding. Within this set of results, once more the variant with TTA integrated maximizes the Recall of the model.

To round-off the series of experiments, this paper also includes tests to assess the efficacy of TTA on a defect segmentation problem. The same Ball Screw Dataset is leveraged again but with segmentation labels that mark the precise location of the defects. As the dataset contains only one type of defect, this is a binary segmentation problem. The outputs of the original image and three augmented images are aggregated, thus providing four class predictions per pixel. The study highlights three configurations for TTA configuration based on the required confidence level of the module – assigning a defect label to the pixel if at least one, two or three class predictions concur, respectively. It is evident that requiring only one out of four class predictions to contain the defect label is the most liberal configuration for predicting defects while requiring three defect predictions out of four class predictions on a pixel is the most stringent. This is a critical design choice that must be driven by use-case requirements.

The results in TABLE 6 show that the application of the TTA module boosts the f1 score. Further, carefully choosing the configuration of the aggregation strategy enables control over the Precision and Recall as well as a balanced option between the extremes.

TABLE 6
ACCURACY METRICS OF THE TTA MODULE APPLIED TO A SEGMENTATION MODEL EVALUATED ON THE BALL SCREW DATASET

Operation	Minimum Votes for Defect Class	Precision	Recall	f1
Baseline	N/A	0.304	0.769	0.436
TTA	1 out of 4	0.194	0.830	0.315
TTA	2 out of 4	0.314	0.75	0.442
TTA	3 out of 4	0.463	0.63	0.532

The results of these experiments validate the

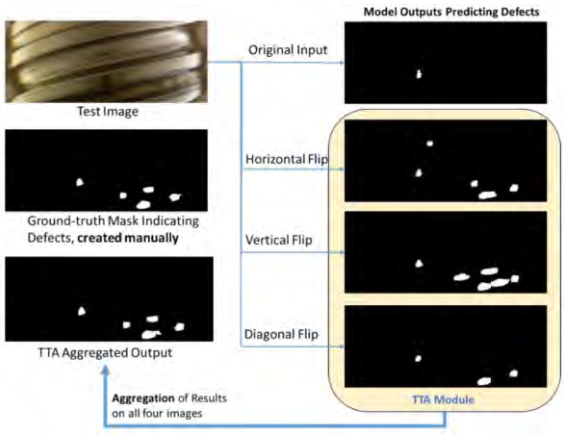


Figure 13. Example of applying TTA to a Segmentation model on the Ball Screw Dataset. The white regions indicate the presence of defects. The model output on the original input image fails to detect most of the defect instances but the final TTA output post-aggregation is a close match to the ground truth that was created manually.

viability of TTA as a control factor between Precision and Recall which can be tweaked as per the use-case requirements.

V. CONCLUSION

This paper explores the use of Test-Time Augmentation in improving the effectiveness of DL models in the domain of asset defect inspection. The paper highlights the finer nuances and considerations of a TTA pipeline and combines them with recommendations to form a general framework for applying TTA to Classification and Object Detection models.

Through multiple experiments conducted on defect inspection datasets, the utility of TTA was established. Further, it was shown that even in challenging use-cases, TTA is useful as a control operator in balancing the Precision and Recall of the DL model. This paper has demonstrated the effectiveness of TTA and described a framework with actionable recommendations that can be employed to boost the accuracy of a wide range of DL models for asset inspection.

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Integration of Blockchain Technology with PLM

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Abstract / Executive Summary - This paper explores the integration of blockchain technology in Product Life Cycle Management (PLM) to enhance the capabilities of the current PLM systems. Integration of blockchain with PLM can enable secure communication between PLM tools of different organizations. It assists in facilitating data sharing and synchronization across multiple organizations even though they have different PLM servers. Blockchain technology with its inherent security, transparency, and decentralized nature can aid in achieving a framework where the customers, and all the stakeholders can cocreate the required product from project conception to disposal. The paper highlights the importance of integrating distributed ledger technology and smart contracts in PLM systems. The methodology section outlines the implementation of blockchain in Beginning of Life (BOL) phase of aircraft product life cycle. It proposes an architecture of Blockchain Information Service (BIS) to enable data communication between different PLM software with the blockchain network. Overall, the integration of blockchain technology in PLM offers improved transparency, collaboration, and data integrity, making it a promising solution for future product development processes.

Keywords - PLM, Distributed Ledger Technology (DLT), Blockchain, Blockchain Information Service (BIS), Smart Contracts

I. INTRODUCTION

PLM is a strategic approach to managing the entire lifecycle of the aircraft from conception to retirement. It aims to optimize the product development cycle, and provide an overview of the progress of the project to the management, to help in taking the important decisions.[1]

Today Aircraft development is complex and require collaboration between multiple organizations. The parts of aircraft are parallelly developed in different organizations in different locations. In this fast and highly dynamics workflows, the PLMs system enables traceability and collaboration among the stakeholders from designer to end users, and to aid in innovation and improve the success rate of a new product introduced. [1]

The PLM needs to support a higher level of customization to suite the type of project and level of digitalization required by a that organization. It helps to collaborate, share, track the progress of project and it illustrate the same to the different stakeholders based on his/her role in the project.

The approach employed in aircraft manufacturing is known as engineering-to-order [16]. This approach is utilized to manufacture aircraft with specific characteristics, such as high technological complexity, a wide range of product variations, substantial involvement of customers in product

specifications, low production volume per unit, and extensive engagement of stakeholders. Furthermore, the product's lifecycle is intricately linked to the product development program and the orders received from customers. Any errors, ambiguities, or misunderstandings that occur during the design phase can lead to significant costs, which are incurred during the manufacturing process and throughout the subsequent stages of the product's lifecycle [6]. These costs can be substantial.

One of the major areas the current PLM should look for is improved integration and collaboration among different stakeholders especially if they are from different organizations and use different PLM tools. These inabilities to integrate a common platform for all the stakeholders might leads to inefficiencies, errors, delays, and increased costs in the product development process. A possible solution is to adopt a more holistic and agile approach to PLM, where all the stakeholders are involved in a continuous feedback loop and can access and update the product information in real time. This would enable faster and better decision making, innovation and quality improvement.

This paper attempts to integrate blockchain technology, a distributed ledger technology, with PLM to develop a transparent, secure, and interoperable PLM tool for the development of Aircraft

II. LITERATURE REVIEW

A. Product Lifecycle Management

Existing PLM tools operate locally and provide support to design teams and provide project managers information on the progress of the projects. They employ centralized servers as specified by the PLM tool providers [14]. The advancement of aircraft development relies on the concurrent development of individual components, which are being worked on simultaneously by various organizations. Specific milestones, such as Critical Design Review (CDR) and Preliminary Design Review (PDR), are established to monitor the progress of aircraft component development [6]. These organizations possess their own PLM tools, housing progress of project within the organization in centralized servers. Present PLM solutions exhibit limited transparency and interoperability across various organizations which uses different PLM software, frequently requiring organizations to operate based on trust without mechanisms to verify claims. Utilisation of cloud servers may address the issues to a certain extent but the with the risk of data security. The prevailing PLM architecture predominantly relies on a "client-server" structure, centralizing access through terminals that do not store data locally.

To address these challenges, a proposed solution involves the development of an industrial PLM platform built upon blockchain technology. This innovative approach integrates industrial blockchain, smart contract functionality, and Internet of Things (IoT) technologies. Blockchain, well known for its transformative impact on the financial sector, boasts several advantageous features, including heightened security, irreversibility, decentralized operation, transparency, and precision [4].

The paper by NAVAIR, USA also explores the use of industrial block chain to track. Maintenance, repair, and overhaul (MRO) operations for a tail hook assembly using SIMBA Chain enterprise platform.[12] The specific use case reduced the complexity significantly in terms of how one might track every part that NAVAIR dealt with. And the paper presents the potential solution to connect transactions from two separate block chain systems, Quorum and Hyper ledger Fabric the latter is used by NAVAIR and formal by OEM (Boeing). The SIMBA Chain code platform was used to architect, design and implement this case at NAVAIR. SIMBA Chain is a comprehensive, fault tolerant, secure environment that focus on providing scalable production enterprise applications.[9] SIMBA Chain code uses Graph based model connects everything by representing relation between entities, connecting versions of smart contracts, and even mapping smart contracts between different blockchains for a single application.

The Project Lifecycle of a part can be classified into 3 stages beginning of life (BOL), middle of life (MOL), and end of life (EOL) [4]. BOL includes design and manufacturing; MOL includes product usage, service and maintenance; and EOL includes the timespan when products are dis-assembled, remanufactured, recycled, reused, or disposed.

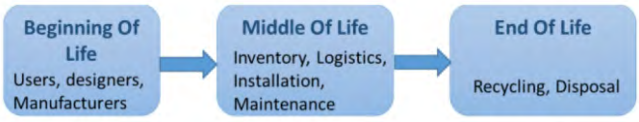

Figure 1 PLM Process

The BOL phase can be further classified into 2 phases as presented in Figure 2: The Design Phase and The Manufacturing Phase.

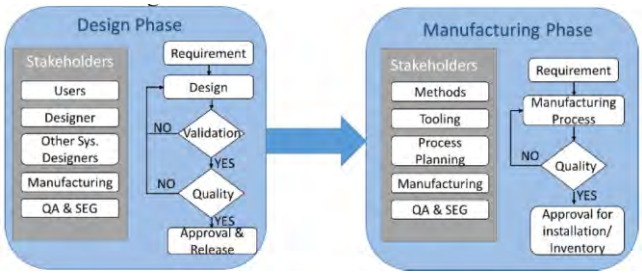

Figure 2 Phases in BOL

The design phase commences with a precise establishment of the end product's objectives and concludes upon the completion of the digital mockup. It encompasses cooperative efforts and cross-functional tasks that engage multiple stakeholders. It represents a phase of project cocreation. The requirements have the potential to evolve regularly, influenced by factors like feasibility and input from various stakeholders. Blockchain technology can be employed to securely store this data, facilitating a reliable source of information.

The manufacturing phase begins after the design is frozen. It is the process of converting the raw material to finished goods. The subsequent chapters discuss the implementation of blockchain in each of these phases.

B. Distributed Ledger Technology(DLT)

A DLT is a type of data structure which resides across multiple nodes, spread across different locations. The data is stored in a decentralized manner and the current state of the data can be captured, and a provision to change that state when new transactions are recorded. A consensus algorithm must be present to ensure that all participants agree and all nodes have the latest copy of ledger [4].

C. Blockchain Technology

Blockchain is a DLT, in which data can be written only with consensus from its members who digitally sign. The data recorded on a blockchain is cryptographically secured with digital signature, that is verified, ordered, and bundled together in the form of blocks [4]. The new block is added once the network participants agree to the current state of the data, based on the consensus algorithm. Each block is timestamped and linked to previous block forming a chain of data. The "append-only" character of the blockchain makes it extremely hard to change the written data (without collision). Satoshi Nakamoto demonstrated the first ever blockchain called as Bitcoin Blockchain marked convergence of a host of technologies which includes timestamp of transitions, peer to peer networks, cryptography, and shared computational power along with new consensus algorithm [10].

Bitcoin was basically designed to work as a currency, aka cryptocurrency, and allowed only basic codes, which are not Turing compete. Vatalik Buterin created another public blockchain "Ethereum" which introduced Ethereum Virtual Machine (EVM), which allowed Turing compete programs aka smart-contracts to be written on the blockchain [13]. This introduced innovations such as decentralized application where multiple peers can verify and run the application on the blockchain. Bitcoin, Ethereum and other public blockchains provide immutability, but may not be suitable for enterprise use cases such as Aeronautical Development Agency (ADA), Defence Research & Development Organization (DRDO), etc.

In order to utilize the benefits of blockchain

technology and also make it suitable for enterprise use-cases, permissioned blockchains have been developed where the access to participate in the blockchain is restricted. A digital identity is mandatory and is required by the admin node to provide permission to the candidate node to participate in the blockchain. Proven permissioned blockchains are Hyperledger Fabric, R3 corda, Multichain, etc.

D. Hyperledger Fabric

Hyperledger Fabric is an open-source distributed ledger platform founded by IBM and later managed by The Linux Foundation. It provides us with a modular architecture with plug and play components such as consensus, privacy, and membership services [14]. As per the Hyperledger fabric architecture, a channel needs to be created for the involved organizations to interact with each other

E. Smart Contracts

Smart contracts are programs that are written, for users to interact with the blockchain. Functions written smart contracts are called by the users to either change the current state of the ledger, or to query data of existing data stored in the ledger. They can be developed considering the existing development processes already in the enterprise including version control, peer review, unit and integration testing, and continuous development and integration pipelines [4]. The smart contracts once developed must be subject to verification by the peers, security audits to ensure its safe usage in the blockchain.

Blockchains like Ethereum, have order-execute architecture where the smart contracts are to be carefully designed in domain specific languages like solidity, so that the peers arrive at consensus. Hyperledger Fabric uses execute-order-validate architecture, where the chain codes do not directly interact with the blockchain but run-in containers such as dockers [14]. This enables the use of standard programming languages like python and java

F. Consensus algorithms

Consensus is the process of achieving agreement among participating nodes, for the addition of new blocks to the blockchain.

"Proof of Work" consensus algorithm used in blockchains like "Bitcoin" requires miners to race with each other to find solution to a complex mathematical problem and broadcast

them to the network, which is verified by the network participants. On successful validation the block is added to the blockchain with certain number of "Cryptocurrencies" as a reward to the miner. The solving can be performed only by brute-force method and is computation intensive [10]. As all miners race and try to solve the problem, it consumes huge amount of electricity and becomes unsustainable [4].

Another consensus algorithm is "Proof of stake" used in Ethereum blockchain requires miners to stake certain number of cryptocurrencies to acquire the rights to mine and add the block to the blockchain. Once the block is verified by the other participants the miner is rewarded with mining fees and gas fees [13].

Consensus algorithms like PoW, PoS are designed for use cases where the participants of the network are unknown and have no trust with each other. It also involves the use of cryptocurrency to reward the miners such that the network is sustainable [14].

For enterprise use cases, the network participants are often identified, trusted, and operate under a governance model that yields a degree of trust. Relying on the identities of the participants, much simpler and cost-effective algorithms like crash fault tolerant (CFT) or byzantine fault tolerant (BFT) consensus protocols can be used [14].

G. Blockchain Information Service

X. L. Liu et al. proposed blockchain information service [1] which is used to connect nodes with the blockchain network. As a middleware, it can not only process the multi-source and heterogeneous data from varied stages in the product lifecycle, but also broadcast the processed data to the blockchain network.

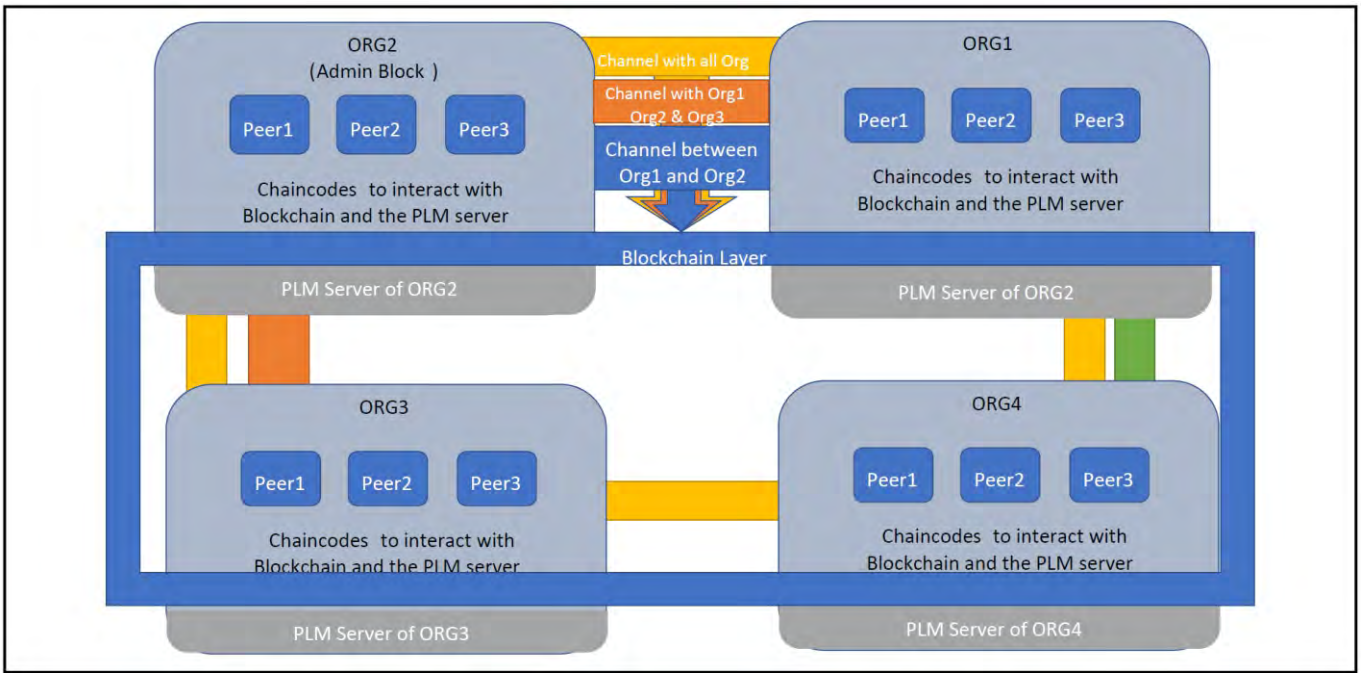

Figure 3 Blockchain Architecture to Integrate Blockchain across multiple organisatuibs

III. METHODOLOGY

This paper attempts to present a conceptual framework to integrate Blockchain with PLM in the BOL phase but provide a brief description of advantages in implementing in MOL and EOL phases.

A. Blockchain Architecture of Proposed system

It is important to design the architecture in such a way that minimum change is made in the existing architecture, to improve adaptability of the system. The organizations have their own PLM servers where the data is stored. Figure 3 presents the proposed architecture for the integration of blockchain with the PLM.

A blockchain layer represented in blue color is added above the PLM server represented in grey color, such that it stores only the necessary information such as design status, date of change, the path of the file on the PLM server and the hash of the file to ensure that it has not been modified once a transaction is made. The peers on each organization interact with the blockchain and PLM server to change its state.

A channel will be created between the organizations that need to communicate and share the data. A Common channel which is common to all the organizations (represented in yellow color) can be created to share/view the data which is to be accessed by all the organizations. When a communication is to be made between two or three organizations; a channel will be made between them. The data that are required to be saved on the blockchains are programmed using the chaincodes that are shared only between those organizations. Any transactions made by the organizations, using the chaincodes are registered on the blockchain which resides on all the organization.

The body who is responsible for the entire project like ADA, can be made as the admin block. The admin block will have privileges, such as to decide if to allow if a certain organization can join the network, nevertheless it will not have any authority to change the existing data on the blockchain without the consent of other participant organizations, or as defined by the consensus algorithm.

B. Design of BIS

Since the blockchain is intended to work between different organizations, with the different PLM software, the BIS is to be designed appropriately. The BIS is designed with majorly 2 parts:

BCinteraction and PLMinteraction.
The BCinteraction is designed to interact and

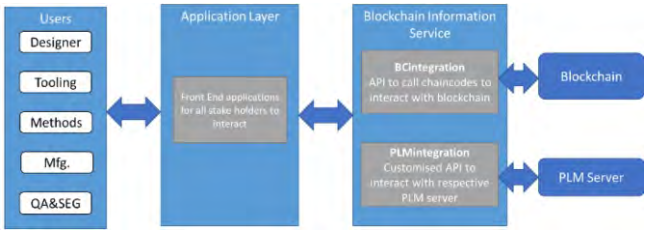

Figure 4 Blockchain Framework in an organization

query information from the blockchain. It is responsible to interact with the blockchain and will have the APIs to call the functions from the chaincode.

The PLMinteraction is responsible to interact with the PLM servers and will have APIs to query, edit and write information on the PLM servers.

The BCinteraction will be common for all nodes in a channel which is responsible for a particular design activity whereas the PLMinteraction will be different for different organizations. It depends on the PLM software that organization uses.

C. Design Phase

Design phase is referred to the phase where the designers and engineers develop the aircraft based on user's requirements.

It requires interactions between different organizations, teams to attain the optimum design. The user's requirement drives the developmental process and any change in them can have significant impact on the project timeline and budget. To ensure transparency and accountability, the requirements and major decisions can be recorded on the blockchain as transactions that are timestamped and digitally signed by all stakeholders. Blockchain can enable different stakeholders, such as engineers, manufacturers, regulators, and customers, to access and update the same information in real time, without compromising data integrity or privacy. This promotes co-creation of the product with a secured environment.

Non-Fungible Tokens (NFT) can be generated and tied for the parts of the aircraft, and attributes can be provided to record its characters and the developmental phase. When the part reaches the design milestone, the respective token's attributes can be updated accordingly by the engineer. The quality validation made on the parts can also be registered, and saved by respective stakeholder and stored on the blockchain.

D. Manufacturing Phase

The design phase is followed by the manufacturing phase, where the designs are finalized, and the components of the aircraft are fabricated from raw materials.

It is essential to monitor each component of the aircraft in the supply chain. It can not only help detect and resolve the inefficiencies in the supply chain but also ensure the quality is maintained for the components. Each operation can be recorded onto the blockchain as a transaction.

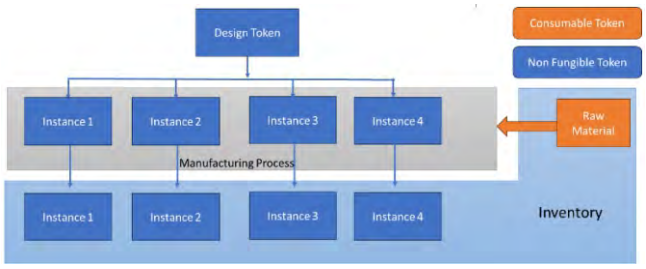

Figure 5 Converting design tokens to Manufacturing tokens

In this phase, each component token from the previous phase is split into smaller units called sub tokens, which are also NFTs but which carry forward the necessary attributes of the parent NFT token form the design phase, corresponding to the number of components produced.

Each Raw material is represented with a consumable token with the properties and the quality certificates associated with it to be attached as the characteristic of the token.

The components as it moves ahead with the manufacturing process, the consumable tokens are utilised as raw materials are utilised and the

same information can be recorded as attributes for the corresponding sub-token. Other attributes of the sub-token include other manufacturing processes, quality certificates, etc.

This will also assist in the Enterprise Resource Planning (ERP) as the record of the available raw material and the consumed raw material is readily available. As the product moves through the different manufacturing phases, the respective tokens are updated. IoTs can be utilised to perform quality checks and automatically update the tokens or the same can be performed manually. A unique ID for each token can be attached and block chain allows for easy track for status of the token, thus the component.

E. Data on Chain

Blockchain is a decentralized system that requires the same data to be stored on multiple nodes. There are certain considerations that are to be made whilst deciding the data which must be on the blockchain. Data privacy and the size of the data are among major concerns.

While the blockchain is a fool proof system to store transactions, organizations must be careful in sharing proprietary information on the blockchain which can include CAD Files, Mesh files, etc. The blockchain is used to verify the current state of the project and all the study data may not be relevant. Those data such as the result a study may be sufficient to verify. The raw research data can be saved in the existing PLM servers and the path, and the hash of the study files can be stored in the blockchain to verify any changes that are made on the files. This not only improves the security of the data on the blockchain but also reduces the amount of data that must be saved on the chain.

With the use of BIS, this interoperability of the blockchain with the existing servers can be enabled.

Depending on different phases of the project, the respective team can mandate the type of data that can be saved on the blockchain

In design phase, only essential data like phase of the project, volume/size, path of the file on the server can be saved in raw format and the files specifying requirements, the actual parts, can be stored as hash of the file.

In the manufacturing phase, details of the manufacturing processes that the part undergoes, the quality certificates can be recorded on the blockchain. This can allow for improved reputation and open regulations and ease the track the status of parts in the workshop.

F. The MOL and EOL phase

The tokens generated from the BOL phase can be easily transitioned to the MOL phase, as the component moves from inventory to aircraft installation. Relevant attributes from the design phase and the manufacturing phase can be assigned to tokens. A QR code, which gives details of the unique address, can be placed on the part to ease the traceability. The maintenance activities carried out, can be recorded on the blockchain. In case of any unexpected failure, inspection of the blockchain can provide details regarding all the activities that is performed on the item.

Blockchain helps in tracking all the activities right from the design phase, until the product is retired.

IV. SCOPE OF USAGE

This section discusses the services that a blockchain based PLM can provide in to an organization.

A. Co-creation service

Prahalad and Ramaswamy proposed the concept of cocreation [10], where the company and the consumers work together to construct the service experience to suit their requirement. One of the challenges is to provide open but secured environment for co-creation.

Blockchain technology can provide a secure, transparent, and decentralized platform for data sharing, collaboration, and verification. It can enable different stakeholders, such as engineers,

manufacturers, regulators, and customers, to access and update the current state of the project in real time, without compromising on data integrity or privacy. This improves the coordination and communication among the parties involved in the design and development process, as well as reduce errors and delays.

B. B. Project Tracking Service

Blockchain technology can enable easy track and verification of the progress of the project real time, by all the stakeholders enabling them to make informed the user, the management can easily track the state of the project and analyses the increment in cost and timeline for incorporating the change in requirement. This can be easily validated by the user, improving trust and transparency in the system. Management will be able to easily be identify the subprojects that do not meet the timelines and take corrective actions to boost the productivity. It can keep track on the commitments made by different organizations/teams and ensure that they comply them.

C. C. Traceability and Provenance Service

Blockchain can also facilitate the traceability and provenance of aircraft components, materials, and software, ensuring quality and compliance throughout the supply chain. For instance, blockchain can record the origin, history and status of each component, material and software used in the aircraft, as well as any changes or modifications made to them. This can help to prevent counterfeit or defective parts from entering the system, as well as to verify the authenticity and performance of the products. Blockchain can also reduce costs and risks associated with data duplication, inconsistency, and tampering, as well as improve the efficiency and security of data transmission and storage. For example, blockchain can eliminate the need for intermediaries or third-party verification services, as well as reduce the amount of data that needs to be stored or transferred. This can save time and money, as well as enhance data security and reliability.

V. CONCLUSION

Blockchain technology is a promising solution for the common challenges that organizations face. By combining blockchain technology with PLM, organizations can enhance their supply chain efficiency, as well as achieve the necessary transparency and security in their system. This is crucial for today's businesses, as they need to operate in a trustless environment, where they can verify the claims of other parties. Moreover, blockchain technology can ensure privacy by restricting the access to information, or using techniques like Zero Knowledge Proof (ZKP). This can help organizations to adopt the emerging technologies and industrial processes, and facilitate the transition to Industry 4.0.

Blockchain is still an emerging technology that faces some challenges and limitations, such as scalability, interoperability, regulation, and adoption. However, it has the potential to transform PLM and create value for all stakeholders involved in the product lifecycle.

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Overcoming Ideation Bottlenecks through Conversational AI

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Abstract / Executive Summary - This paper examines the potential of a conversational AI-enabled Active Ideation Interface as an innovative tool during ideation. Its purpose is to assist novice designers in overcoming the initial latency in generating ideas due to mental blocks. With their limitations and rigid rules, traditional ideation techniques often fail to address these hurdles. This study investigates a more dynamic, interactive, and contextually responsive approach, actively involving an AI model in the ideation process. Using a large language model (LLM) from the Artificial Intelligence (AI) domain, an ideation interface was built on top of a sketching medium. It leverages the power of GPT-4 (Generative Pretrained Transformer) to provide relevant and creative responses conversationally. At the heart of this interface's design is integrating active ideation using GPT, thereby fostering continuous dialogue-based interaction, contextsensitive conversation, and idea mapping. It bridges a crucial gap left unaddressed by conventional ideation methods. The research methodology employs a comparative analysis, pitting the proposed AI-enabled Active Ideation Interface against widely used ideation techniques. A pilot study involved participants generating ideas for design problems using traditional methods and the GPT interface under identical conditions. The study's key parameters, Fluency (Γ), Novelty (η) and Variety (υ), were used to evaluate the ideas produced by participants in both approaches quantitatively. The findings highlight the advantages of adopting a GPT-based Ideation over traditional methods. By transcending the limitations of conventional tools and fostering a more engaging ideation process, this interface serves as an innovative framework for nurturing creativity among novice designers. This paper identifies the shortcomings of traditional ideation techniques and champions the potential of an Aienabled Active Ideation Interface as a game-changer in product design, particularly for aspiring young designers. It represents a promising step toward revolutionizing idea generation in design, emphasizing the role of AI in unlocking human creativity.

Keywords - Artificial Intelligence (AI), Generative Pretrained Transformer (GPT), Ideation, Large Language Model (LLM), Product Design

I. INTRODUCTION

In an increasingly complex and technology-driven world, creativity and innovation have become essential skills in product design. Generating many novel ideas quickly is not only valued and but also expected from designers [1]. However, this creative ideation process can often be challenging for industrial product designers. Novice designers face this as an even more daunting task of expanding their creative capacity, especially in the early idea generation phase [2]. This is often attributed to young designers lacking the experience to develop novel ideas because of a mental block resulting from repeated cognitive fatigue during ideation [3].

Most commonly used ideation techniques, such as brainstorming, SCAMPER, random word techniques, etc., often serve as rules or guidelines to be followed rather than active participants in the creative process [4]; this poses limitations and

challenges, especially in facilitating diverse idea generation. Considering these constraints, a more proactive, engaging, and responsive tool is required to stimulate creativity, generate multiple novel ideas and ease the ideation process. Recognising this issue and striving to provide a solution, this study investigates the potential of using a novel tool to foster creativity and facilitate the generation of diverse ideas among emerging designers. The proposed tool employs a large language model called Generative Pretrained Transformer (GPT) embedded as an Active Ideation Interface. It engages designers and helps stimulate their imaginative capabilities through continuous conversation. The AI-enabled Active Ideation Interface serves as a tool for idea generation and as a mentor, introducing a fresh perspective and providing inspiration during the creative process. This significantly enhances novice designers' abilities to generate novel ideas, catalysing their creative growth and pushing the boundaries of design in an increasingly complex world. Thus, this dynamic ideation process contrasts with the static nature of traditional techniques.

Given the potential of this AI-driven tool to revolutionise ideation processes, the present research focuses on comparing its efficiency to traditional methods. The tool generates a higher volume of ideas and ensures a diversity of ideas that can solve the stated problem. This is tested by a methodology that involves a comparative study between the proposed tool and traditional ideation methods. In summary, the study aims to illuminate the potential of AI-enhanced ideation, helping novice designers unlock their creative abilities, produce novel ideas, and ultimately shape the future of design.

II. LITERATURE REVIEW

A. Creativity and Ideation

According to Reference [5], creativity is widely defined as the "development of novel and useful concepts," a definition well-accepted by the research community. In product design, ideation methods often encourage designers to think expansively and set aside judgments of feasibility. However, it is essential to note that the notion of the usefulness of an idea is essential during conceptualization [6]. This is particularly true for product design, which inherently serves practical purposes and solves real-world problems [7]. Designers seek inspiration to stimulate their minds into creative thinking to generate ideas. Creative thinking is a fusion of divergent thinking and convergent thinking. Solutions arising from convergence can serve as a precondition for divergence, which can pave the way for high-level convergence. Each convergence leads to new ideas, facilitating step-by-step problem resolution [8].

In product design, ideation is imperative during the early stages of the design process. It is the process of generating, developing, and communicating abstract, ambiguous, and imprecise ideas. Idea generation is vital for exploring the design solution space in conceptual design. It encompasses various elements of the thought cycle, from creative formulation to innovative manifestation, aiming to generate numerous, diverse, novel and valuable ideas. The effective generation of novel and useful design ideas remains a pressing concern for novice designers [2].

The designer operates within a dynamic "design space," a three-dimensional cognitive environment where functional blocks, initially connected by links, evolve from conceptual forms into tangible 3D objects. This approach allows for flexibility and the potential emergence of new ideas [9]. Designers then go on to reevaluate these ideas and make necessary changes. Regardless of the methodology employed, the design process typically begins with defining the overall product function and breaking it into manageable subfunctions. Ideas are sought for these subfunctions, ultimately determining the concept through combining the ideas devised for these subfunctions [10].

Regarding creativity and ideation, various definitions exist. Still, for the present context, we define a creative idea as "an assertive statement that describes 'what' part of the solution and needs to

be both novel and diverse". Assessing the degree of creativity in an idea typically involves measuring how much it deviates from existing solutions and emphasizes the significance of originality.

B. Text as a Mode of Description of Ideas

Words, images, and symbols are essential triggers for generating ideas. Unlike in the past, where designers relied on written information during ideation, contemporary designers frequently uses keywords for online resource retrieval. Thus, recognizing the value of the text in transforming thinking modes is crucial in design cognition research [11]. Developing a high-level design language, often called a vocabulary or taxonomy, is crucial in enabling a systematic approach to ideation. Text plays a significant role in this process, as keywords continuously stimulate individuals to determine their next steps during self-dialogue. This shift in thinking mode is observed daily and is particularly prominent during the design process, where designers spend considerable time searching for information to address design problems. Using keywords when searching for online resources is common among designers, allowing them to retrieve relevant information related to their design tasks [10].

The text also serves as a tool for reflection and idea formation in design activities. Designers reflect on their ideas, aiding in developing new ideas and facilitating the design process. The habit of searching with text has become ingrained in designers, prompting researchers to explore the relationship between keyword thinking and idea generation. Before initiating a search, designers carefully consider potentially relevant words to their design task. This suggests that thinking precedes searching for information. During ideation, keyword search behaviour can lead to four modes of association: word shifting to image association, word shifting to word association, image shifting to word association, and image shifting to image association [12]. External information, such as natural objects, visual inspiration, and language terms, can also contribute to the ideation process [13].

A creative design idea is an original, appropriate, and nonobvious idea related to a design solution's function, behaviour, or structure [14]. Therefore, high-level design language facilitates systematic ideation. Text, in the form of keywords and information retrieval, stimulates designers during ideation and aids in problem-solving. Reflection on the textual modality based description of ideas triggers various modes of association and inspires creative thinking.

C. Traditional Ideation Techniques and their Pitfalls

Ideation techniques are integral to the design process and provide designers with structured pathways to foster creativity. Over time, product design has developed and employed a wide range of ideation techniques. Although effective in guiding and facilitating creativity, these traditional techniques serve predominantly as rules and frameworks to follow rather than as active contributors to the ideation process. While effective in guiding and facilitating creativity, these techniques impose the onus of creativity and originality on designers.

The table I below summarizes the essential details of each traditional ideation technique [3], including their descriptions and limitations regarding their contribution to generating creative ideas.

The table I highlights the traditional ideation techniques employed in product design. Each technique offers a unique approach to stimulate creativity and waits for innovative ideas to spur into the designer's mind. Exploring these traditional ideation techniques reveals their foundational principles and inherently unveils a uniform thread of limitations prevalent in these techniques. These methodologies furnish designers with procedural structures for nurturing creativity and cultivating ideas, albeit without direct involvement in the ideation process. While these techniques have proven effective in channelling creativity, they often lack the dynamic support necessary for novice designers. The responsibility for originality and diversity in generating novel ideas essentially rests with the designer. Therefore, these tech-

TABLE I. COMMON IDEATION TECHNIQUES AND THEIR LIMITATIONS

Technique	Description	Limitations
Brainstorming	Encourages idea generation in groups and innovation through collaboration	Limits individual creativity due to fear of judgment, criticism, or peer pressure
Mind mapping	Assists in visualizing the brainstorming process but does not actively generate ideas	Does not contribute to ideation directly, leaving creative burden on the designer
Random / Trigger Word	Involves using random words as triggers for new ideas	Only prompts designer to derive links between word and problem
Synectics	Comprehensive method using analogies and metaphors to generate innovative ideas	Requires significant time and effort to facilitate and may not always yield practical ideas
Prototyping	Helps explore, test, and visualize different solutions	Dissociates from the original context and does forces fitting of concepts to problems
SCAMPER	Guides designers to think differently by examining a product from various perspectives	Leads to superficial and incremental ideation rather than truly innovative ideas
Design thinking	A user-centric method to empathize with users, understand their needs, and develop problem-solving ideas	Sets the stage for a problem-solving mindset, does not provide creative spark
Morphological Chart	Assists in systematic exploration of new combinations and innovations	Becomes complex and overwhelming when dealing with numerous variables and options, potentially hindering idea generation
Analogous thinking	Helps draw comparisons between unrelated things to create innovative concepts	Relies on the designer's knowledge to find relevant analogies, limiting its applicability.
Bio-Inspiration	Draws inspiration from nature and biological systems for novel and sustainable design solutions	Provides a potent source but does not create ideas itself
Idea-Inspire	A systematic approach using abstraction, analogies, and principles from nature for design ideation	Provides a tool facilitating creativity but does not independently produce creative ideas
SWOT analysis	Helps identify strengths, weaknesses, opportunities, and threats related to a project	Static tool that creates a platform for analysis but does not assist in generating ideas
Six Thinking Hats	Encourages thinking from different perspectives	Guiding methodology that does not facilitate direct ideation
Heuristic Ideation	Stimulates creative ideas using heuristics	Results in ideas that lack depth or feasibility, as it emphasizes quick, intuitive thinking
Five Whys	Primarily used to understand cause-effect relationships	Oversimplifies complex issues and miss underlying systemic problems
TRIZ	Delivers a systematic approach to solving problems by identifying contradictions and providing solutions	Provides a framework for problem-solving, does not actively contribute to creative ideation

niques often fail to actively aid or engage novice designers who encounter hurdles during the early stages of idea generation. Despite their proven efficacy in steering creativity, these methods generally lack the dynamism to support designers during their initial ideation. Even though they enable unconventional thinking and provide systematic procedures, all these methods possess limitations, encompassing potential judgment biases, constraints in visual representation, a requirement of a wide knowledge base and the prerequisite of expertise on the part of the designer.

D. Problems in Existing Ideation Techniques

The ideation phase of the design process still poses challenges for inexperienced and even experienced designers. The quantification and formalization of generating ideas are active research areas, with many formal methods yet to be realized as computational algorithms. Existing tools focus on stimulating creativity and providing inspiration, leaving designers with limited options for creating quality ideas [10]. The success of an idea often relies heavily on personal experience and innate ability. Although brainstorming and morphological analysis are widely used, they rely on individual bias and experience [15]—other ideation methodologies, including bioinspired design and design-by-analogy, provide guidance and inspiration. Traditional ideation approaches are mostly based on design principles and design thinking methodologies, while program-based ideations automate and integrate the advantages of different ideation approaches. On the other hand, data-driven ideation relies exclusively on analysing existing data obtained from design experiments [2].

Ideally, the ideation phase should result in diverse potential designs because multiple variations increase the likelihood of finding novel and innovative solutions [16]. However, engineers often fixate on specific design options early, limiting the variety of designs. This phenomenon is called Design fixation, where designers adhere blindly to a limited group of ideas, negatively impacting creativity and reducing the diversity and quantity of generated design concepts [13]. Knowledge and experience can contribute to design fixation, as our preconceived notions restrict the design thinking process. Novice designers may struggle to generate diverse concepts and often exhibit this phenomenon early in design. Experience and expertise play a significant role in creative idea generation, and designers progress through different levels of expertise, although this progression is not necessarily linear [3]. Therefore, existing ideation techniques face challenges in providing concise methodologies applicable to designers of various experiences. Current Ideation methods, driven by knowledge and experience, hinder creativity and pose a challenge in guaranteeing novel ideas.

Given these limitations, there is an imperative need for an ideation tool that offers a more immersive, engaging, and stimulating role in idea generation rather than serving as a static framework. Herein lies the potential for integrating artificial intelligence like large language models, specifically GPT-4. An AI-based tool, such as the proposed GPT-based Active Ideation Interface, could dynamically and contextually interact with designers, pushing them towards expanded realms of thought and igniting more inventive ideas. The purpose of this paper is not to undermine the value of traditional ideation techniques, as they remain pivotal in design. Instead, it is prudent to acknowledge the emergence and integration of AI models in ideation as a promising development to redesign the creativity and innovation landscape in product design, particularly for designers at the inception of their careers. This type of ideation technique is known as Computational Ideation.

E. Computational Ideation

Matching user perceptions with intelligent product design is a significant challenge due to the multidisciplinary knowledge required by the designer to create potential ideas. Generating many ideas and identifying the most novel and valuable ideas is beneficial to developing novel solutions in complex systems and competitive markets [17]. However, processing, reviewing, and assessing many design concepts can be challenging.

Research in computational ideation explores methods such as deep learning for generating ideas and making recommendations on existing solutions. Automatically generating such ideas can be used as a catalyst to generate additional variants through non-computational creative techniques [18]

The advent of digital big data has opened up novel avenues for idea generation by harnessing the potential of large datasets. These data-driven approaches substantially expand the design landscape and facilitate the exploration of innovative and feasible designs. Simultaneously, artificial intelligence (AI) algorithms have emerged as valuable tools to inject inspiration into the ideation process, offering stimuli in the form of direct solutions, analogies and bio-inspired knowledge. Among these AI tools, large language models (LLMs) such as GPT (Generative Pre-trained Transformer) have gained prominence for their ability to generate diverse forms of original text [19]. Conversational AI, a subset of generative AI, has the potential to play a significant role in the creative ideation process during the early stages of product design. The rapid advancements in AI and generative machine learning, exemplified by technologies like GPT, stress the need to examine these tools to facilitate the generation of novel solutions. It is imperative to ascertain how such AI systems can be tailored to align with human values, especially considering these technologies are designed to emulate intelligent human agents [19].

A salient feature of Conversational AI systems such as GPT is their reliance on natural language interaction, permitting users to engage with them through open-ended chat-based dialogues, resembling human-to-human interactions [19]. Utilizing computational ideation tools, such as GPT, can significantly aid in generating many solutions and identifying exceptionally creative ideas. GPT uses big data and AI algorithms to enrich the ideation process by granting access to extensive repositories of knowledge resources that even experienced designers are not equipped with. This study delves into computational ideation using a conversational AI system - GPT, and explores how this technology can intertwine with ideation.

III. PASSIVE VS ACTIVE IDEATION

A. Passive Ideation

Novel ideas generated during ideation form the foundation for innovative and impactful products. However, many existing ideation techniques are passive. Passive ideation is defined as one which enables only one-way communication, putting the burden on the designer's mind to generate ideas, thereby limiting the potential of designers. The following are some of the limitations of passive ideation methods.

1) **Lack of Engagement:** Traditional ideation methods often lack the level of engagement necessary to inspire and ignite the creative process. While valuable, brainstorming or mindmapping techniques can become monotonous. This passive approach may hinder designers from fully exploring unconventional or breakthrough ideas, restricting their creativity.

2) **Limited Collaboration:** Many traditional ideation methods are primarily based on personal thought discovery, restricting the power of collaboration. While individual thinking is essential, harnessing the collective intelligence of a diverse group can lead to more innovative concepts. Passive methods may not facilitate effective collaboration, resulting in missed opportunities for cross-pollination of ideas and fresh perspectives. Collaboration also requires discussion with experts and peers. Humans, with their diverse personalities, may hinder the generation of novel ideas as they can be biased towards their ideas.

3) **Slow Iteration:** Passive ideation methods often require significant time investment, slowing the iterative design process. Waiting for individual ideas to be shared, analysed, and consolidated can delay progress and hinder the exploration of alternative concepts. Designers need a more agile, active approach that allows for rapid idea generation, testing, and refinement.

B. Active Ideation

Active ideation is characterised by a natural, dynamic, unbiased collaboration between a designer and the ideation method, facilitating creativity and critical thinking. This continuous conversation-driven approach serves as a solution to address the limitations of passive ideation methods. By embracing active ideation, designers can overcome the constraints of passive ideation techniques, encouraging diverse perspectives and interactive engagement throughout the ideation process.

1) Enhanced Engagement: Active ideation is characterized by a higher level of engagement from the medium. Incorporating textual stimuli, dynamic prompts, and immersive experiences, designers are encouraged to think more creatively, break free from conventional thinking, and explore novel solutions to design challenges.

2) Dynamic Idea Exploration: An active ideation medium encourages designers to think beyond traditional boundaries and experiment with various ideas through multiple quick revisions. By providing the ability to have natural conversational dialogues with an omniscient, designers can explore different solutions and generate multiple design options that would not have been possible.

3) Data-Driven Insights: Active ideation can collect and analyse conversational data during the ideation process, providing designers with valuable insights into the effectiveness and feasibility of different concepts. By leveraging real-time answers, designers can make informed decisions, prioritise ideas, and identify emerging patterns, leading to more diverse and detailed ideas.

Traditional passive ideation falls short in the fast-paced nature of contemporary design practices. Designers must embrace active ideation tools that provide the fullest engagement and rapid iteration to the problem at hand. By integrating Aienabled tools such as GPT and creating an active ideation scenario, designers can unlock their creative potential, explore unconventional ideas, and develop innovative concepts more efficiently. As the design landscape evolves, an AI-enabled active ideation interface becomes increasingly vital, enabling designers to stay at the forefront of innovation and create products that genuinely resonate with users' needs and desires.

IV. RESEARCH QUESTIONS (RQ) AND METHODOLOGY

RQ1. What is the impact of an AI-powered ideation tool on transforming the passive ideation scenario into an active, engaged and creative scenario?

The current landscape of conventional ideation tools typically provides designers guidelines or rules to follow, providing little assurance of generating genuinely innovative ideas. This approach can be described as a passive ideation scenario, where the burden of generating creative and novel ideas rests solely on the designer, often leading to cognitive demands and potential mental blockages. Although brainstorming facilitates collaboration among multiple people, many other traditional tools lack active participation and are silent. Consequently, there is a need for an active ideation scenario that replicates an interactive conversation with an expert designer, providing guidance and suggestions without the biases that can arise from human judgment, as observed in brainstorming sessions.

Methodology for RQ1: Large language models, exemplified by OpenAI's GPT, have gained significant popularity for their ability to engage in human-like conversations and provide expert opinions. This study uses the OpenAI API to integrate the GPT model to create a chatbot within an ideation interface developed using Unity and C# programming. The effectiveness of this interface in facilitating active ideation is quantitatively assessed by measuring the fluency and novelty of generated ideas within a given time frame. This research aims to provide insight into the potential benefits and limitations of employing such an active ideation interface for enhancing creative idea generation among designers.

RQ2. How do we stimulate creative thinking in novice designers to mitigate mental blockage and cognitive fatigue during early ideation?

Novice designers transitioning from academia to the professionalrealm often encounter mental blockage when faced with real-world problem statements requiring innovative solutions. Despite being equipped with conventional ideation tools and techniques learnt during their academic journey, these designers may experience a phenomenon known as a designer's mental block, akin to writer's block. This condition arises from prolonged cognitive fatigue that causes the brain to stagnate or remain confined within a limited solution space. Therefore, there is a critical need to stimulate creativity in novice designers without compromising their autonomy to generate various solutions independently, providing support instead of simply providing predetermined solutions.

Methodology for RQ2: The GPT model offers a temperature setting that promotes answer randomisation, influencing the model's level of creativity in response to input questions. Conversations between the user and GPT are stored in contextual buffer memory, facilitating continuous, contextaware interactions. An integrated sketching medium is also developed, combining GPT into a unified interface that lets designers quickly express their ideas through doodles, text, or idea sketches. The research evaluates the variety and similarity of ideas generated by this approach.

V. AI INTERFACE FOR ACTIVE IDEATION

A. GPT – A Conversational AI

The Generative Pre-Trained Transformer (GPT) is a stateof-the-art large language model (LLM) developed by OpenAI. As a language model, it has been trained to predict the next word in each piece of text, enabling it to generate coherent and contextually relevant sentences [20]. The Generative Pretrained Transformer (GPT) model by OpenAI has undergone a complex training regime that involves three core stages: unsupervised pretraining (USPT), supervised fine-tuning (SFT), and reinforcement learning from human feedback (RLHF).

The training of GPT occurs in three stages. In the initial stage, the model learns from vast internet text data using unsupervised learning, gaining a broad understanding of human language, including grammar, world facts, reasoning abilities, and some biases. Then, in the supervised fine-tuning (SFT) stage, human supervisors review and rate model outputs based on example inputs, helping the model refine its behaviour. Finally, reinforcement learning from human feedback (RLHF) fine-tunes the model further by creating a reward system through human rankings of responses. These stages collectively train GPT to produce human-like text while adhering to safety and ethical standards, striking a balance between raw performance and controlled behavior [21].

The GPT model has undergone four evolutions thus far, each more advanced than the previous, with the latest model being GPT-4. With each subsequent version, these models increased in size, complexity, and capability. Due to its vast size and extensive training, the model can answer questions, write essays, summarise texts, and even translate languages - essentially any task that involves predicting the next word in a sentence [22]. In the context of ideation and problem-solving, its ability to generate diverse and novel ideas and implement them cohesively and purposefully makes it a potential game changer in product design.

B. Benefits of using GPT as an Ideation Tool

In the dynamic field of product design, the ideation stage plays a crucial role in developing innovative and impactful products. With the advent of artificial intelligence (AI), designers can now access powerful tools that can serve as active ideation interfaces, inspiring creativity and generating ideas. GPT, an advanced language model powered by AI, offers designers an active ideation scenario that stimulates creativity through conversational interaction. By engaging in a dialogue with GPT, designers can articulate their design challenges, ask questions, and receive prompt and personalised responses similar to brainstorming with multiple people, but instead with an expert omniscient. This interactive approach sparks new

ideas, encourages exploration of different design possibilities, and helps overcome mental blocks. The advantages of GPT as an active ideation interface include:

1) Inspiration and Knowledge Expansion: GPT can provide designers with a wealth of information, offering insights from various industries, design principles, and emerging trends. It acts as a virtual collaborator, inspiring designers by presenting alternative perspectives and facilitating cross-pollination of ideas.

2) Rapid Iteration and Feedback: Designers can quickly iterate their ideas by asking for feedback from GPT. The model's ability to understand and respond to nuanced queries allows for immediate evaluation and refinement of design concepts. This accelerates the ideation process and enables designers to explore broader possibilities.

3) Contextual Guidance: GPT can guide designers by asking relevant questions, challenging assumptions, and offering suggestions. By providing contextual guidance, the model helps designers think critically, consider multiple factors, and refine their design ideas with a holistic perspective.

C. Design of an Active Ideation Interface

An active ideation interface was designed and developed using a conversational AI system-GPT embedded in a sketching medium, as shown in Fig. 1. GPT provides the backbone for natural language generation, allowing the interface to respond and generate creative ideas based on user input. The sketching medium provides a fast means for rapidly putting down ideas. By integrating these, the interface provides the designers with a conversational and intuitive platform, as GPT stimulates idea generation. This combination empowers designers by augmenting their creative thinking, supporting brainstorming sessions, and improving the overall ideation process by fusing advanced AI technology into ideation.

1) Pre-training the GPT for the role of an Expert Designer: The GPT model was pre-trained to serve as an expert designer for active ideation, which

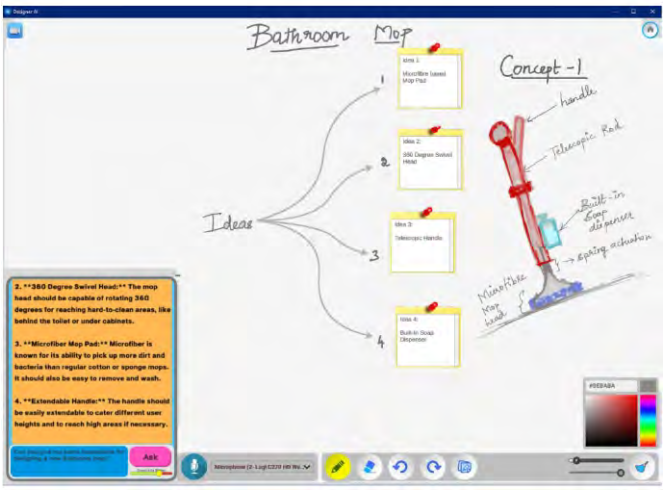

Fig. 1. Active Ideation Interface Designed with GPT over a Sketching medium

involves initialising the model with a vast and diverse corpus of text data from various online sources, including product design-related documents, books, articles, and forums. This exposure to a wide range of design concepts, methodologies, paradigms, and approaches allows the model to develop a broad understanding of the design field. This process can also enable the model to learn the domain-specific language, creative design ideation, innovative problem-solving skills, and various design thinking strategies applied by expert designers. By doing so, the pre-training phase essentially imparts the language model with the essence of design expertise, allowing it to generate insightful, contextspecific, and creative ideas in the design ideation process. Therefore, this model training stage transforms the GPT model into an AI tool that brings an expert design perspective, actively participating and contributing to the ideation process.

2) Transfer Learning & Contextual Buffer Memory: A contextual buffer memory was created and used in context continuation tasks, such as design ideation sessions. This can significantly enhance the value and performance of the GPT model to continue engaging in context-aware conversations for a longer duration. This method of learning from an earlier conversation to keep the context of a current conversation is termed Transfer Learning. The contextual buffer memory is designed to store the earlier conversations in a

JSON file so that it can be used to initiate the next design session. Here, transfer learning is defined as a concept where a model uses previous conversations as knowledge in a new but related context, enabling continuity in conversation. In the case of an ideation session, if a designer pauses the session and returns to it later, the contextual buffer memory helps the GPT model to remember the context of the previous session and proceed from where it was left off. It effectively 'recalls' the conversation thread of earlier sessions and continues the ideation process according to the pre-existing context. This ability to maintain continuity despite interruptions can significantly benefit the design ideation process, ensuring that insights or ideas from previous sessions are not lost, and the creative thinking flow remains consistent. Therefore, contextual buffer memory as a form of transfer learning is an essential feature developed and used in this interface. This was done to support designers in maintaining consistent, fluent, and efficient idea generation over multiple sessions.

3) Temperature as a measure of creativity: The GPT model employs an element known as ”temperature” to adjust the randomness or creativity of the model's responses. Temperature is a parameter that affects the probability distribution of the model output. The temperature setting in the GPT model serves as a valuable parameter for controlling the response level of creativity generated during design ideas. By adjusting the temperature value, designers can influence the degree of randomness and novelty in the model output. A higher temperature setting leads to more diverse and imaginative responses, encouraging exploring unconventional ideas and promoting creative thinking. On the other hand, a lower temperature value produces more deterministic and focused responses, aligning closely with known patterns and preferences. This flexible temperature setting enables designers to fine-tune the balance between generating innovative concepts and adhering to established design conventions, catering to specific project requirements, and capturing a desired level of creativity in the ideation process.

VI. PILOT STUDY

Thirty participants were selected for an in-lab experimental investigation in a pilot study, as shown in Fig. 2. These participants were all enrolled as Master's students specializing in Product Design and Engineering, representing a cohort of emerging young design students. To facilitate the study, the participants were randomly divided into six groups, each assigned a specific design problem statement. Before embarking on the design task, all participants received comprehensive training in utilising various conventional ideation methods, and a practice session was conducted to ensure their familiarity with the techniques. Ethical considerations were upheld, and proper consent was obtained from all participants for using the study's outcomes in further research endeavours. The study comprised two distinct parts, denoted Part A and Part B, each serving specific research objectives that will be elaborated upon in subsequent sections. Following the completion of the experiment, the ideas generated by the groups were meticulously assessed and analyzed, with the results and findings detailed in the subsequent section of this report.

Fig. 2. Participants performing the study

A. Hypothesis Formulation

H1: GPT promotes an active ideation scenario.

In an active ideation scenario, the level of involvement among designers during the ideation process, characterised by uninterrupted idea flow and continuous dialogue, is a significant measure. One way to assess an ideation tool is by quantifying the number of ideas generated within a specific period, which indicates fluency in ideation. The impact of active ideation can be further evaluated by examining how well the generated ideas align with meeting the requirements of the given problem, thereby measuring the novelty of the

generated ideas. Thus, fluency and novelty emerge as critical measures to assess the activeness of the ideation tool.

H2: GPT aids in overcoming mental blocks.
Past experiences, events, and various stimuli often ignite creativity in human thinking. These triggers can encompass visual imagery, real-world encounters, or verbal information. This study explores how conversations, used as creative triggers through GPT, can stimulate the brain to overcome ideation bottlenecks. The quantitative evaluation of these approaches can be accomplished by assessing the variety in the ideas generated. The variety metric indicates how the ideation tool successfully breaks the designer's mental block, encouraging the creation of distinct ideas that differ. It signifies that the designer can navigate through a range of solution spaces.

B. Design of the Study
A protocol was designed for a pilot study, providing the initial assumption that the GPT would be a supportive aid during ideation. Our intuition is that the GPT will support novice designers on their journey of idea exploration. At the same time, we also believe that GPT will be able to provide a diverse set of ideas with different levels of creativity in a matter of seconds. But no data were available to corroborate or deny our intuition. Therefore, a controlled user study was performed to find necessary proof that compared conventional idea generation techniques for a given design task and the use of GPT for ideation. The details of the study are as follows.

Part A: Ideas were generated for an unseen design task using Traditional Ideation Techniques such as Brainstorming, Random Word, SCAMPER, Synectics, and Analogous Thinking within 20 minutes. In Part A, there is no usage of GPT.

Part B: Participants were instructed to use the AI-enabled active ideation interface for idea generation. Proper training and practice sessions were held to familiarise them with the new interface and the use of GPT.

C. Design Task
The following design problem statements (PS) were assigned to each group.

- Problem Statement 1: Solution for Segregation of Wastes for Effective Waste Management
- Problem Statement 2: Solution for Footwear Disinfection and Cleaning for Improved Hygiene and Safety
- Problem Statement 3: Solution for Enhancing Household Dish Cleaning Efficiency and Sustainability
- Problem Statement 4: Solution for Enhancing Comfort and Efficiency for Prolonged Standing in Queues
- Problem Statement 5: Solution for Creating an Interactive Bird Feeding Product to Foster Mental well-being in Elderly Individuals Staying at Home
- Problem Statement 6: Solution for Convenient Umbrella Drying and Storage

Each problem statement was well-defined in detail, stating the background, user needs, challenges and objectives.

D. Performance Metrics
The assessment of idea generation effectiveness encompasses various commonly employed metrics, including novelty, variety, quality, and quantity [23]. Generating a higher quantity of ideas can lead to the emergence of higher-quality design concepts [24]. As defined by [23], Novelty pertains to the degree of uniqueness of an idea, while variety encompasses the extent of exploration within the solution space. Novelty (η), therefore, signifies the divergence of an idea from existing concepts, while variety (υ) encapsulates the richness of diversity among ideas. Fluency (Γ) denotes the quantity of ideas generated within a specified period. The assessment of ideas is essential, as not all generated ideas progress beyond the ideation phase into further development. It is essential to recognize that post-ideation typically entails a concept development and evaluation stage, wherein concepts generated from multiple ideas undergo meticulous evaluation and filtration for subsequent implementation.

E. Assessment of Generated Ideas

From the user-centred design perspective, it is essential to emphasize that end-users assessment of design concepts carries equal significance when compared to expert evaluations, as typically conducted through methodologies such as the Consensual Assessment Technique (CAT) [1]. This emphasis arises from the direct correlation between user perception of ideas and their likelihood of product adoption. Empirical research has illuminated that user perceptions of ideas can be markedly influenced by how these ideas are presented and the fidelity of representations. Consequently, it becomes imperative to exercise meticulous care to mitigate potential biases that may arise during the evaluation process. In light of this, to evaluate the design ideas generated in both Part A and Part B of the study, they were submitted for assessment to design researchers affiliated with the Department of Design in renowned institutions in India, such as IIT Delhi, IIT Guwahati, IIT Bombay, and IISc Bangalore. A total of 80 responses were collected. The subsequent section will delve into a comprehensive analysis of these responses. The design researcher fulfilled dual roles, serving both as expert evaluators and end users of the problems stated under the design task.

VII. RESULTS AND DISCUSSION

A. Fluency (Γ)

The study's results reveal noteworthy findings regarding idea generation fluency. Specifically, when examining the number of ideas generated within the specified time, it becomes apparent that Part B yielded a significantly higher number of ideas than Part A. This increase in idea generation is visually represented in Fig 3, which clearly illustrates that the number of ideas generated for each problem statement using GPT-based Ideation was nearly three times greater than those generated using traditional ideation methods. These findings emphasise the effectiveness of GPT-based Ideation in overcoming the initial challenges associated with idea generation, particularly those related to mental blocks. By facilitating a more prolific output of ideas, this approach empowers designers to break free from the confines of their usual solution space, thereby encouraging the exploration of unconventional and innovative concepts.

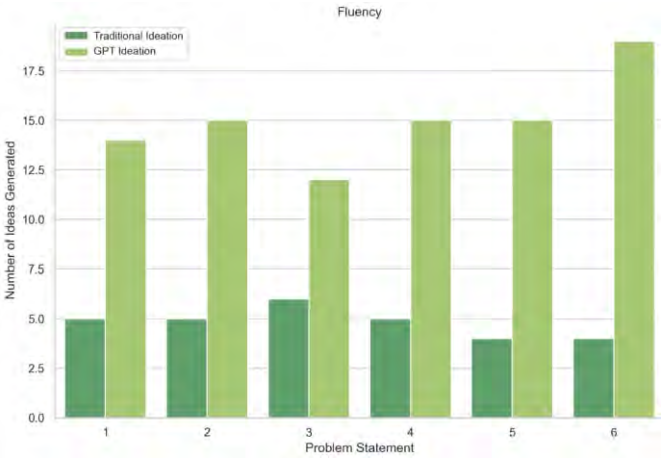

Fig. 3. Bar plot of Fluency (Γ) - No. of Ideas Generated during Part A and Part B

B. Novelty (η)

Hypothesis H1 posits that GPT promotes an active ideation scenario. We employ two critical measures to validate this hypothesis: fluency and novelty in the ideation process.As depicted in Fig. 4, the analysis of novelty ratings indicates a substantial preference for GPT-based ideation over traditional ideation methods, as assessed by experts. The ratings were collected on a 1 to 5 Likert Scale, with 1 representing the least novel ideas and 5 signifying highly novel ideas. The average rating for Part A stands at 2.5, while Part B achieves a notably higher average rating of 3.86. This discrepancy underscores the uniqueness of ideas generated through GPT-based ideation is approximately 1.5 times greater than that achieved through traditional ideation techniques. This disparity in novelty can be attributed to the extensive knowledge database upon which GPT is trained. Even the most seasoned designers, let alone novice designers, may not possess such a vast knowledge resource. Traditional design education often emphasizes the skill of visually representing ideas through sketches, leaving the generation of ideas predominantly reliant on the designer's cognitive abilities. GPT disrupts this conventional paradigm by offering designers cognitive augmentation whenever required, resulting in a notable increase in the novelty value of generated ideas.

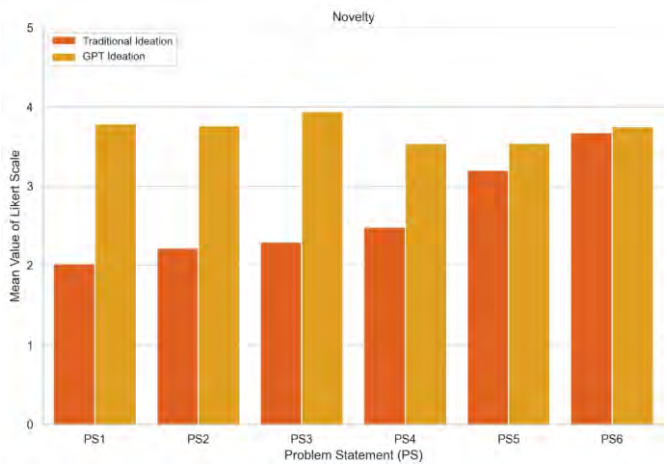

Fig. 4. Bar Plot of Novelty (η) - Uniqueness of Ideas in Part A and Part B

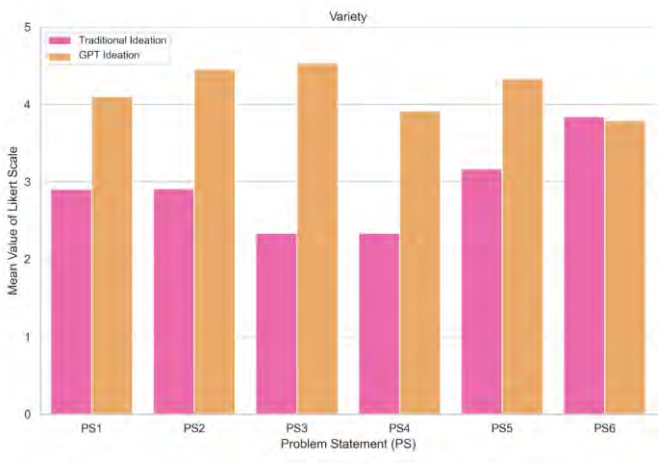

Fig. 5. Bar Plot of Variety (υ) - Diversity among Ideas in Part A and Part B

C. Variety (υ)

The examination of the diversity of generated ideas, as illustrated in Fig 5, underscores a consistent trend favouring GPT-based ideation over Traditional Ideation Techniques. Notably, the diversity in ideas generated using GPT consistently surpassed that achieved through traditional methods. It is worth mentioning that the traditional ideation techniques exhibited notable resilience, maintaining competitiveness with GPT, particularly evident in the case of Problem Statement 6. This can be attributed to the specific traditional ideation method employed by that particular group. In this instance, for Problem Statement 6, the group utilized the Synectics technique, known for its ability to disengage the designer from the problem's immediate context, thereby encouraging the exploration of unconventional and imaginative solutions.

One particular fascination is the remarkable and consistent diversity of ideas generated by GPT across all problem statements. The ratings obtained for Part B were significantly higher than for Part A. This phenomenon can be attributed to GPT's extensive training across a multitude of domains. In contrast, the human brain is typically specialized in storing knowledge related to a particular domain. GPT, on the other hand, draws from a diverse array of domains, effectively functioning as a second brain with a profound understanding of various facets of the world. This broad knowledge base empowers GPT to curate solutions for a given problem from many disciplines, thereby fostering a higher diversity in the generated ideas.

D. Validation of Hypothesis-1

Hypothesis H1 posits that GPT promotes an active ideation scenario. We employ two critical measures to validate this hypothesis: fluency and novelty in the ideation process.

Firstly, fluency in ideation is a pivotal aspect of an active ideation scenario. It is characterized by the uninterrupted flow of ideas and a continuous dialogue among designers. The previous discussion regarding the study's results, specifically the comparison of idea generation between GPT and Traditional Ideation Techniques, supports the assertion that GPT fosters fluency in ideation. The average number of ideas generated within a specified time significantly favoured GPT-based ideation. Part B achieved an average of 15 ideas compared to the 4.833 ideas generated in Part A. This notable increase in idea generation indicates a higher level of involvement and idea flow facilitated by GPT. It substantiates the claim that GPT actively contributes to the ideation process by promoting a more prolific and fluid exchange of ideas among designers.

Secondly, the novelty of generated ideas is another critical measure to assess the impact of active

ideation. In an active ideation scenario, the generated ideas should exhibit a high degree of novelty, indicating a departure from conventional solutions. The results from the study support this aspect as well. The ratings provided by experts consistently favoured GPT over Traditional Ideation Techniques in terms of novelty. The Box plot analysis, as depicted in Figure 5, reveals a striking consistency in the ratings provided by expert design researchers for the novelty of ideas across all problem statements. The ratings consistently fall within a narrow range of 3.5 to 4.5, underscoring a unanimous consensus among experts. This consensus reinforces the notion that all experts concur on the significant enhancement of novelty observed in the ideas generated by GPT. This alignment with the active ideation scenario demonstrates that GPT encourages the exploration of unconventional and innovative concepts, thereby enhancing the novelty of generated ideas.

The measures of fluency and novelty in the ideation process, as evidenced by the study's results, effectively validate Hypothesis H1, affirming that GPT indeed promotes an active ideation scenario. The increased fluency in idea generation and the higher novelty of ideas generated through GPT-based ideation align with the characteristics of an active ideation scenario, highlighting the valuable contribution of GPT to the ideation process.

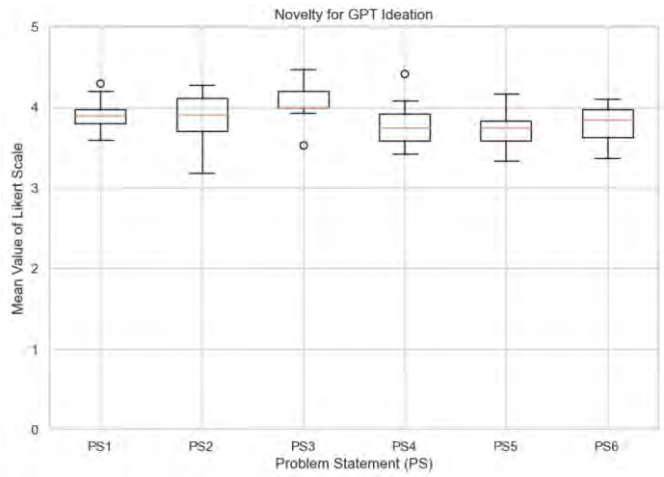

Fig. 6. Box and Whisker Plot for Novelty in Part B (GPT Ideation)

E. Validation of Hypothesis-2

Hypothesis H2 posits that GPT aids in overcoming mental blocks. To substantiate this hypothesis, we employ variety in the ideation process as a critical indicator of the ability to overcome ideation bottlenecks and stimulate creative thinking. Variety in ideation is a key metric that reflects how an ideation tool can effectively assist designers in breaking through mental blocks and generating diverse and distinct ideas. In the context of our study, the results presented earlier in this analysis provide compelling support for the assertion that GPT facilitates overcoming mental blocks. The comparison of the diversity in ideas generated between GPT and Traditional Ideation Techniques showcases a significant advantage in favour of GPT-based ideation. The average rating for Part A in terms of variety was 2.91, while Part B achieved a substantially higher average rating of 4.195, approximately 1.4 times higher. This considerable increase in variety directly demonstrates that GPT empowers designers to navigate through a diverse range of solution spaces, effectively breaking down mental barriers that might otherwise limit ideation.

The measure of variety in the ideation process, as evidenced by the study's results, effectively validates Hypothesis H2, confirming that GPT indeed aids in overcoming mental blocks. The significant increase in the variety of ideas generated through GPT-based ideation highlights its capacity to stimulate creative thinking, enabling designers to break free from ideation bottlenecks and explore a broader spectrum of innovative ideas.

VIII. CONCLUSION AND FUTURE WORKS

This study has shed light on the transformative potential of Conversational AI systems, particularly GPT, in idea generation and creative problem-solving. Several key insights and contributions emerged through a comprehensive examination of the results and findings presented in this research.

First and foremost, the study has demonstrated that GPT significantly enhanced the ideation process by promoting an active ideation scenario.

The metrics of fluency and novelty in idea generation provided compelling evidence supporting this assertion. This aligned with active ideation characteristics and reinforced the value of GPT as a creative tool. Secondly, the study has corroborated that GPT aided in overcoming mental blocks, thus fostering creative thinking. The measure of variety in the ideation process was a pivotal indicator of this capability. Its efficacy in breaking down mental barriers and promoting diverse and distinct ideation was proven. This outcome highlights GPT's role as a catalyst for innovative thinking and a solution to ideation bottlenecks.

Furthermore, the study acknowledges the importance of evaluating ideation tools from a user-centered design perspective. It underscores the significance of incorporating enduser evaluations alongside expert assessments, as user perceptions play a pivotal role in the adoption and success of a product or solution. In summation, this research illuminates the transformative potential of Conversational AI, particularly GPT, in idea generation and underscores the need for continued exploration and integration of AI-driven solutions in the creative design process. By enhancing ideation fluency, promoting novelty, and aiding in overcoming mental blocks, GPT emerged as a valuable asset for designers and innovators seeking to unlock new horizons in creative problem-solving. Therefore, designers can embrace and harness the capabilities of AI-driven ideation tools to fuel the next wave of innovative solutions and designs.

Drawing from the findings of this preliminary investigation, the immediate task at hand involves refining the performance of the LLM model. This can be achieved by meticulously finetuning the model, supplying suitable prompts, and establishing a generalized framework for generating ideas. As the AI model begins to generate a substantial volume of ideas, the conventional CAT-based idea evaluation method may prove inadequate due to the sheer volume of data. This presents a unique challenge that necessitates the development of innovative evaluation strategies. Future research endeavours will, therefore, primarily focus on this area. The objective is to devise novel evaluation methodologies capable of effectively processing and assessing the large quantity of ideas generated by the AI model. This will not only streamline the evaluation process but also enhance the overall efficiency and accuracy of the model in generating and ensuring novel solutions for a given design problem.

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Configuration and Customization of a PLM Software for the Computer-Aided Design (CAD) Data Management

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Abstract - The Design and Simulation Lifecycle Management (DSLM) system is implemented at the Structural Technologies Division, CSIR-NAL, in association with the system integrator. Product Lifecycle Management (PLM) software 'Teamcenter' is considered. Considering the present & future Aerospace programs, a unique sixteen-digit numbering system is proposed for the in-house designed/bought-out parts, and the same is implemented in the Teamcenter application through customization. This customization also supports defining the standard parts like fasteners, etc. Considering the best practices across the aerospace programs, the general and manufacturing attributes are defined for each of the parts/assemblies, and the same is implemented in the Teamcenter application through configuration. General attributes have information like part numbering system details, design center, etc. Manufacturing process attributes have information like material specification, stock details, heat treatment processes, material finish, inspection method, etc. Computer-Aided Design (CAD) modeling software like CATIA V5, SolidWorks, and AutoCAD are tightly integrated with the 'Teamcenter' application. Based on the current practices, the drawing title block is customized to provide details like drawing number, part/assembly name, material specifications, the person(s) responsible for the drawing approval process, weight, etc. Teamcenter application is configured to update some of the drawing title block attributes automatically by pooling the values from the respective CAD part attributes list. The drawing approver names and the approved dates are automatically updated in the drawing title block by referring to the respective drawing approval workflow process. Teamcenter is also configured to export the product structure details into the predefined NAL Engineering Bill of Material (EBOM) template format. This paper presents further information regarding the configuration and customization of the Teamcenter application used for design data management.

Keywords - CAD, DSLM, PLM, Teamcenter, Customization

I. INTRODUCTION

Structural Technologies Division, CSIR-NAL contributes to the Civil & Defence Aerospace programs of the country and plays a key role in the design of aircraft. An initiative is made at the division to implement the product lifecycle management system, as the current process and related data are controlled manually. In this regard, the design and simulation lifecycle management system is implemented on the Product Lifecycle Management Software 'Teamcenter' platform in association with the system integrator. Teamcenter application is configured and customized implementing the user/organization specific requirements for the ease of process and data management.

II. COMPUTER-AIDED DESIGN (CAD) DATA MANAGEMENT

The implemented Design and Simulation Lifecycle Management (DSLM) System on the Teamcenter Platform is tightly integrated with Computer-Aided Design (CAD) modeling software like CATIAv5, AutoCAD, and SolidWorks [1]. In general, CAD software supports a large number of data files. These application data files can also be managed from inside a Teamcenter session. The

relevant Teamcenter functionalities are populated within the CAD tool interfaces and thus simplify the interactions with the data files. Design teams can quickly search for CAD parts, assemblies and drawings. CAD parts and assemblies created in the Teamcenter integrated CAD tools can be viewed in the Teamcenter viewers without accessing their native CAD tools. Teamcenter viewers also supports various functionalities like markup, measurement, sectioning, etc. and thus help in reviewing and approving of the parts & drawings. Teamcenter also supports peer to peer conferencing for ease of decision making. The integration also enables users to reduce the amount of time they spend trying to find and share design information, as well as eliminate unnecessary change orders by ensuring that everyone is working with the latest design information. Teamcenter uses data objects to represent product data such as parts, assemblies, specifications, etc [2]. The default names of these data objects assigned by Teamcenter do not carry any significant information. However, it's a standard practice across the OEMs to follow a standard part/drawing numbering system such that it will carry the critical identifying information. Considering the best practices across the Aerospace programs, a unique 16-digit numbering system for CAD parts/drawings is defined. This unique numbering system carries essential information such as project number, variant, major/minor assembly numbers, part numbers, etc. and provide downstream benefits by helping individuals/departments to identify & track the parts in an efficient way. Considering the best practices across the aerospace programs, the general and manufacturing attributes are defined for each CAD part, a template is defined for the Engineering Bill of Material (EBOM), and arrived at the drawing template with a customized title block.

Product Lifecycle Management Software 'Teamcenter' provides several interfaces, including a rich client interface, a Web-based thin client interface, and a Business Modeler IDE (BMIDE). Teamcenter is based on a client-server architecture. Both the client and server layers can be customized. The client is the user interface (UI) layer and is built and customized using the Java language (rich client) or JavaScript (thin client) and other methods. The server layer can be customized using the Integration Toolkit (ITK) and the C++ programming language. The Business Modeler IDE (Integrated Development Environment) is a tool for configuring the basic functionality and for customizing the data model of Teamcenter installation. BMIDE is used to create Business objects, Classes, Attributes, Lists of values, Options, and Rules. The Teamcenter application is customized and configured to address the above-mentioned CAD data management capabilities and the details are discussed in sections III and IV respectively.

III. CUSTOMISATION OF TEAMCENTER APPLICATION FOR CAD DATA MANAGEMENT

In general, organisation specific requirements may not be able to implement completely using the out of box solution provided by PLM software and calls for configuration and/or customisation of the software for ease of data and process management. An in-depth knowledge of the PLM software is essential to understand the requirements and implementing the same through configuration and/or customisation of the software. However, it is advisable to minimise any such configuration/customisation as this call for an extra effort to implement as well as during migration of the PLM software from existing version to higher version.

Implementation of the proposed numbering system for CAD parts and assemblies calls for the customisation of Teamcenter application. The process of customizing 16-digit part numbering starts with the installation of Java in the Teamcenter development environment, and for this process, Java version 1.8 is utilized. Developing, testing, debugging, and deploying Java projects require the use of an Interactive Development Environment (IDE) tool such as Eclipse. Java offers a wide range of frameworks such as Spring, Struts, and Spring Boot for software development. Spring framework is considered in this customization phase and the creation of a new Spring project

within the Eclipse environment is shown in Fig. 1. The Java installation was added to the project's build path, as shown in Fig. 2. In order to establish communication between the Teamcenter application and a Java project, Teamcenter dependency plugins are added to the project as shown in Fig. 3. The aforesaid steps will ensure that the environment for creating new code is ready and enabled us to make customized user interface layouts for the creation of CAD items i.e. NAL, Bought-out, and Standard as shown in the Figs. 4, 5, & 6 respectively. NAL item type refers to the in-house designed CAD part/item which follows the unique 16-digit part numbering system as mentioned earlier. Bought-out item type refers to the CAD part/item supplied by the external agency like customer, supplier, etc. Bought-out items will also be specified with the 16-digit number apart from the reference source & number details. Standard item type refers to the classified standard CAD parts like nuts, bolts, etc. Standard items will be specified with only the reference standard and the number. This part numbering definition enables the users to clearly categorize the parts into in-house designed parts, bought-out parts and standard parts as considered in the product design. A sample code of user interface layout creation is shown in Fig. 7.

The proposed CAD numbering system carries important information such as project number, variant, major group, sub-group, batch replacement, etc. which are project-specific and predefined while creating the project in the Teamcenter application. The project creation in the Teamcenter application is customized to meet NAL practices, which allows capturing the project relevant information like project name, number, description, etc. along with CAD relevant information as shown in Fig. 8.

While creating the CAD item, the user is allowed to select the project from the list of predefined projects created in the Teamcenter application. Upon selection of any particular project, all the project-relevant information required for the CAD part numbering system like variant, main group, sub-group, etc. will be populated within the user interface layout so that the user can select the appropriate input and continue with the creation of CAD item. The sample codes for getting the required information from the Teamcenter application and populating the same in the user interface layout are shown in Figs. 9 & 10 respectively.

The user interface layout is enabled with event-driven functionality for each input field/element, and the listeners are added which react to every change and thus display the current CAD part number to the user while creating the new CAD item. The sample code showing the functionality of the listener is shown in Fig 11. Also, it is considered that users cannot create a duplicate CAD part and get the error message while doing so.

The Teamcenter application is provided with a customized menu and sub-menus helping to create the proposed CAD items. The codes developed are successfully tested in the developmental environment of the Teamcenter application and implemented in the Teamcenter production environment for regular usage.

IV. CONFIGURATION OF TEAMCENTER APPLICATION FOR CAD DATA MANAGEMENT

CAD parts general and manufacturing attributes are defined and implemented by configuring the Teamcenter application using the BMIDE module. These attributes are defined in the BMIDE forms with unique property names and storage type definitions. The storage type may be string or numeric. Separate forms are created for the general attributes and manufacturing attributes. Some of these attributes will accept the user input values and some of them require users to select among the listed values. The list of values can be added to attributes by defining new LOVs using the BMIDE extension project. BMIDE forms with the definition of general and manufacturing attributes are shown in Figs 12 & 13. These properties can be defined as mandatory inputs or optional inputs. This configuration needs to be deployed in the Teamcenter application. Configuration is such that, these general and

manufacturing attributes forms will be part of any new CAD item allowing the users to update the forms with the relevant CAD item information. General attributes will have information on the part numbering system details, persons responsible for the part approval process and design center, etc. as in Fig. 14. The attributes like persons responsible for the part approval process are non-editable by the users and are updated automatically by the respective drawing approval process implemented in the Teamcenter application.

Manufacturing process attributes will have information like material specification, stock details, manufacturing tolerances, heat treatment processes, CAD part/assembly weight, etc. as in Fig. 15.

The engineering bill of materials (EBOM) is a type of bill of material that defines the product as designed. It contains the list of items, parts, components, sub-assemblies, and assemblies in the product designed by engineering. In general, CAD software supports the automated generation of the Engineering Bill of Materials (EBOM). However, considering the best practices across the aerospace programs, a template is defined for the EBOM using MS Excel, which will provide information like part number & name, quantities required, calculated weight, raw material specification, and stock details with the total quantity required, etc. Teamcenter Structure Manager displays the product structure/assembly in a multilevel indented list format. Teamcenter is also configured to export these product structure details into the predefined NAL EBOM template format, as shown in Fig. 16.

Considering the best practices, the drawing template as shown in Fig. 17 is defined with details like drawing number, part/assembly name, manufacturing tolerances, material specifications, the person(s) responsible for the drawing approval process, weight, etc. Some of the drawing title block attributes will be updated automatically by pooling the values from the respective CAD part attributes list. The drawing approver names and the approved dates are automatically updated in the drawing title block by referring to the respective drawing approval PLM workflow process. This kind of automation ensures that the probable errors due to manual intervention in filling those attributes is completely eliminated. The typical drawing approval workflow process is shown in Fig. 18.

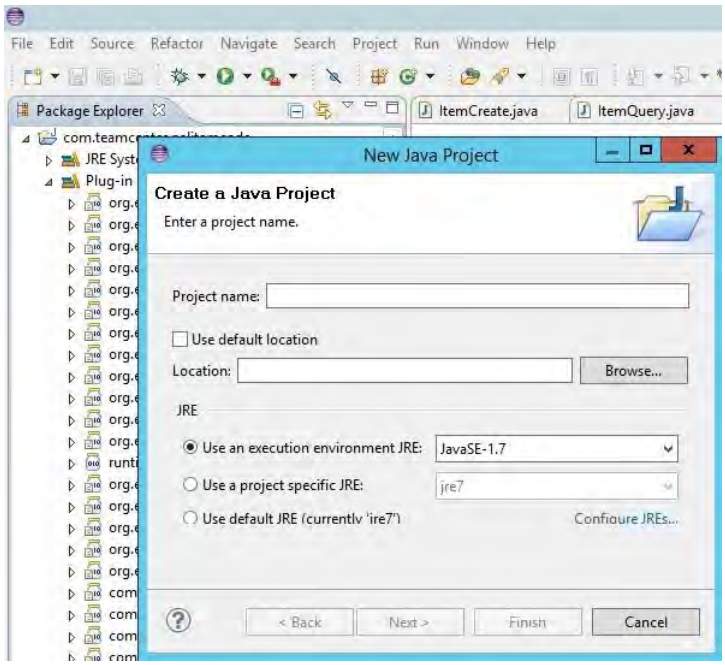


Fig. 1. Sample Spring project creation in Eclipse

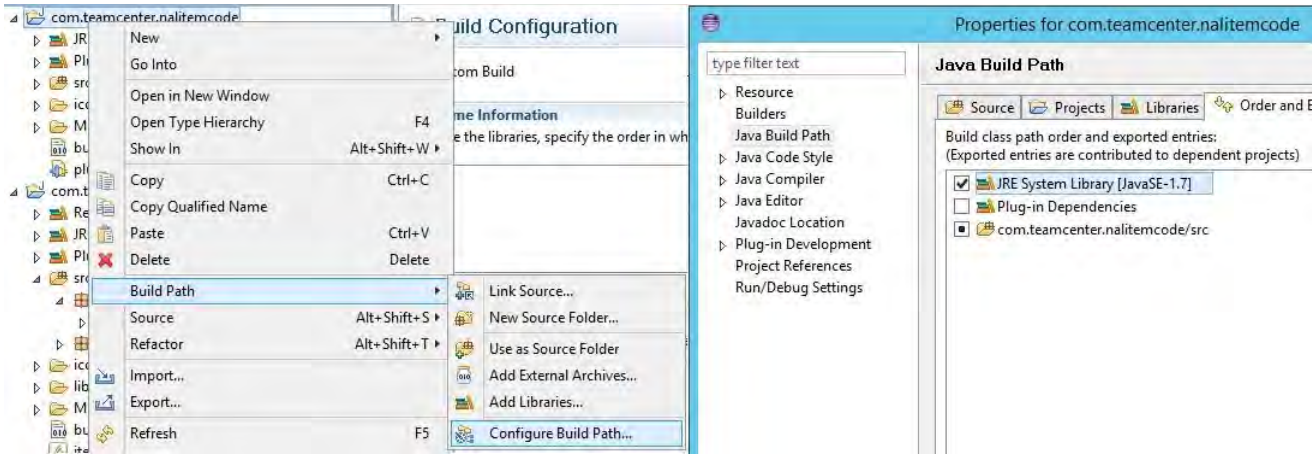


Fig. 2. Build path configuration for Java project

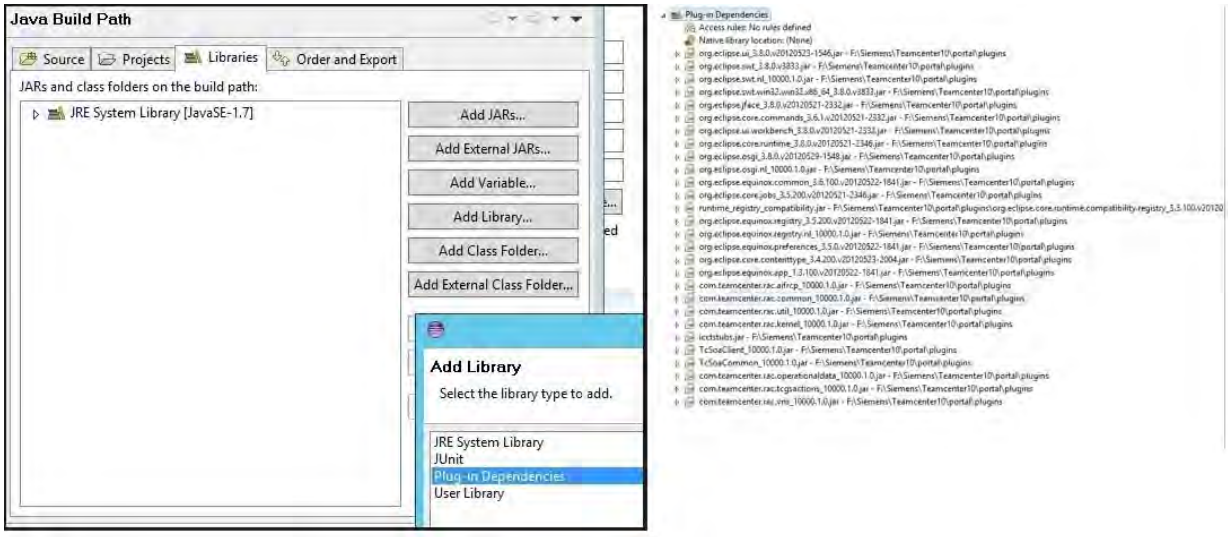


Fig. 3. Adding dependency plugin

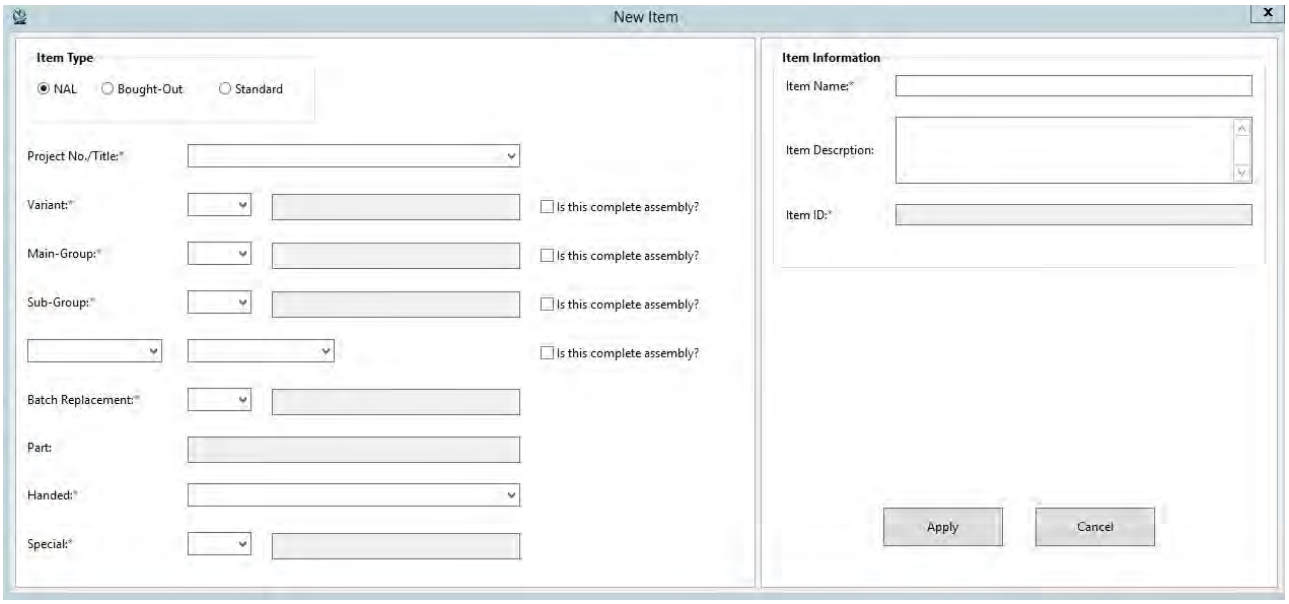


Fig. 4. User interface for NAL CAD item

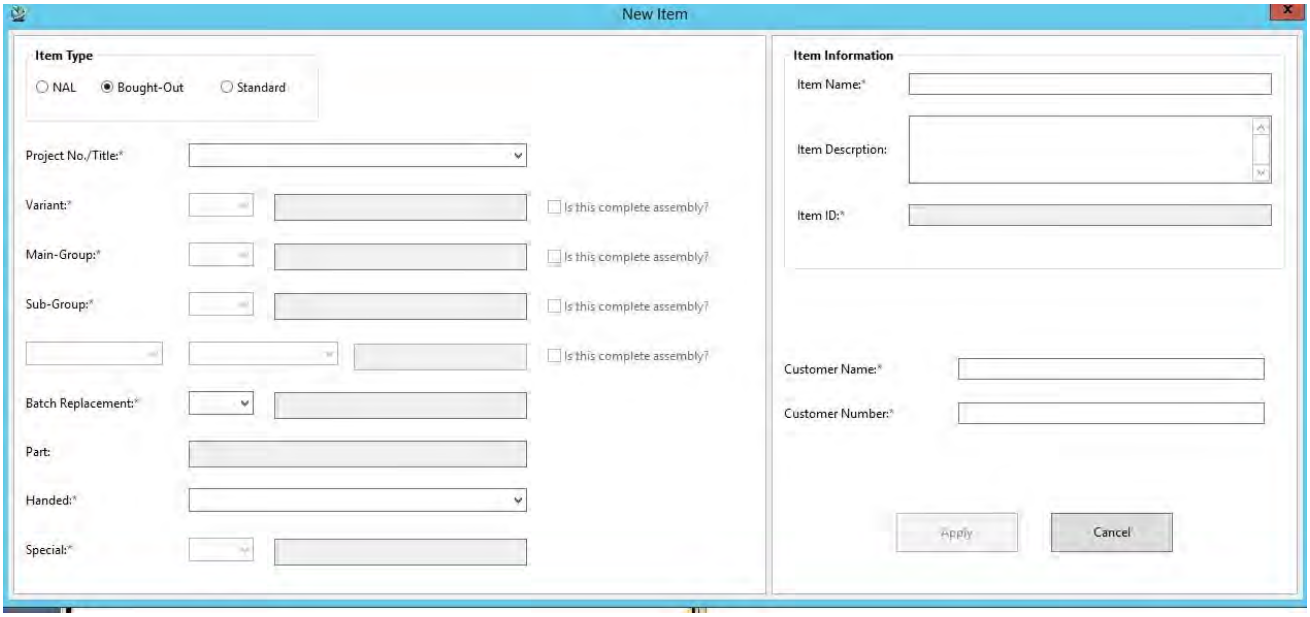


Fig. 5. User interface for bought-out item

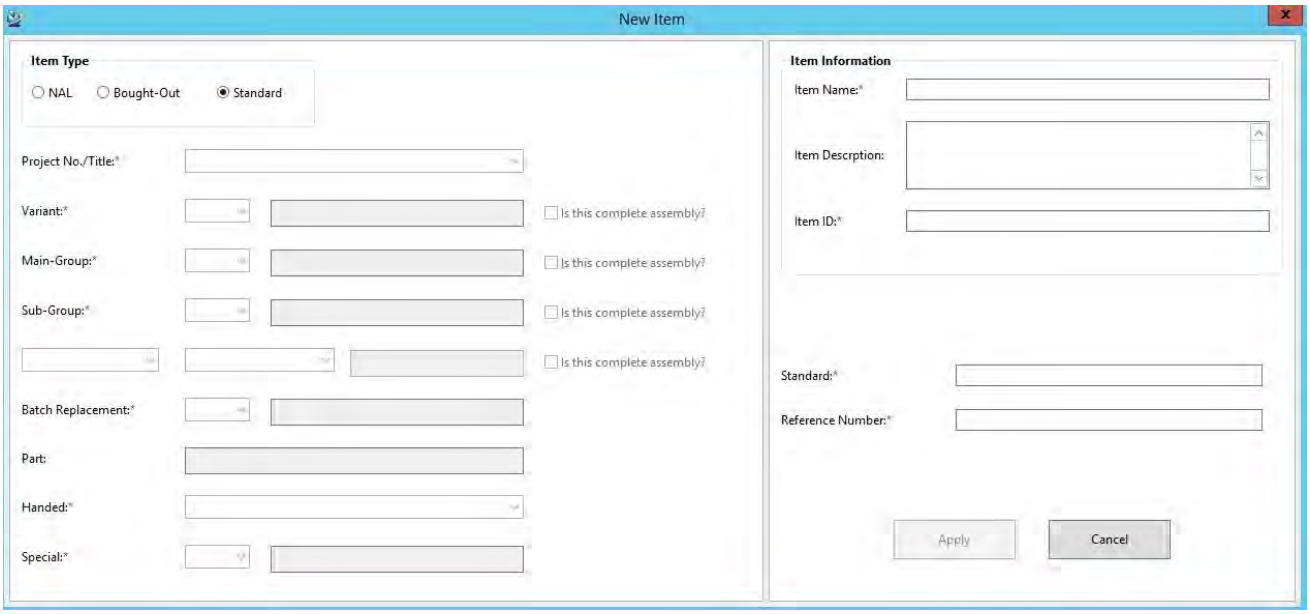


Fig. 6. User interface for standard item

```
// ##########################################        NAL Radio Button      ############

btn[0] = new Button(ItemType, SWT.RADIO);
btn[0].setBounds(20,20,40,25);
btn[0].setText("NAL");
btn[0].setSelection(true);

// ##########################################        Bought-Out Radio Button       #####

btn[1] = new Button(ItemType, SWT.RADIO);
btn[1].setBounds(75,20,80,25);
btn[1].setText("Bought-Out");

// ##########################################        Standard Radio Button     #########

btn[2] = new Button(ItemType, SWT.RADIO);
btn[2].setBounds(170,20,80,25);
btn[2].setText("Standard");

// ##########################################        Project/Title     ##################

styletext[0] = new StyledText(shell, SWT.NONE);
styletext[0].setEnabled(false);
styletext[0].setBounds(30,90,105,15);
styletext[0].setEditable(false);
styletext[0].setText("Project No./Title:*");
styletext[0].setBackground(color[0]);
stylerange[0] = new StyleRange(styletext[0].getText().length()-1,1,color[1], null);
styletext[0].setStyleRange(stylerange[0]);


combo[0] = new Combo(shell,SWT.READ_ONLY);
combo[0].setBounds(175,86,130,25);
combo[0].setItems(projectlist);
```

Fig. 7. Sample Java code for User Interface layout

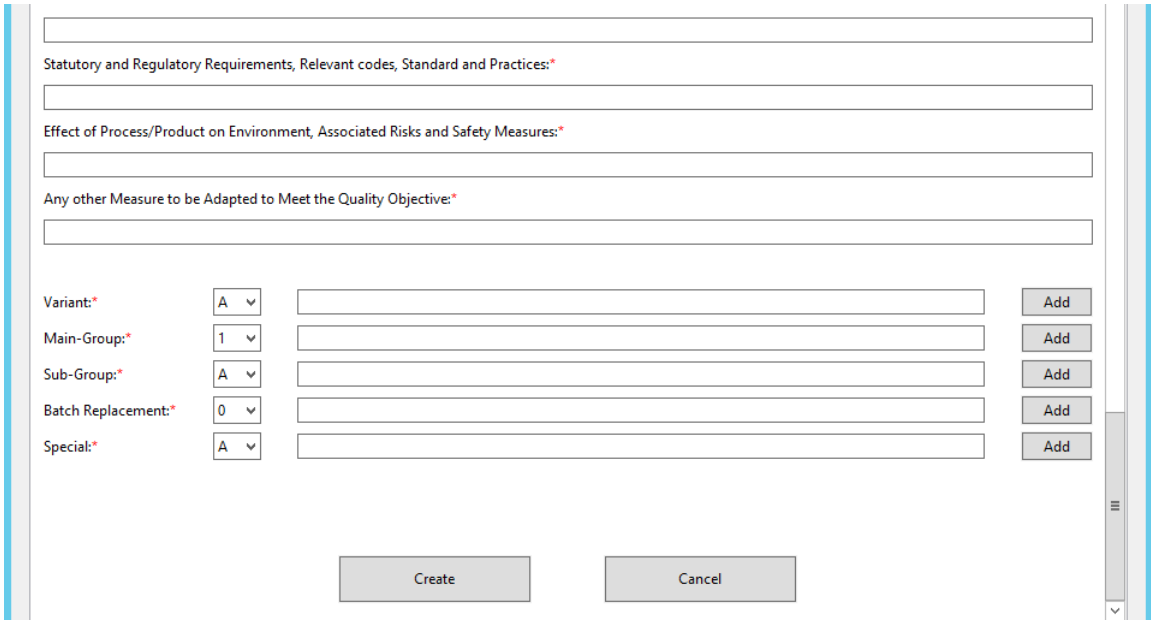


Fig. 8. CAD information capturing while project creation

```
// ####################################        User Based Project List        #######################

public String[] userBasedProjectList() {

    try {
        tccomponentquerytype = (TCComponentQueryType) session.getTypeComponent("ImanQuery");
        componentqueryproject = (TCComponentQuery)tccomponentquerytype.find("UserBasedProjects");
        if(componentqueryproject != null)
        {
            String type[] = {"ID"};
            String s11[] = {user.getUserId()};

            imancomponentcontextlist = componentqueryproject.getExecuteResultsList(type, s11);
            int projectFound = componentqueryproject.count(type, s11);

            projectlist = new String[projectFound];

            if(projectFound != 0)
            {
                TCComponent componentOfElements[] = imancomponentcontextlist.toTCComponentArray();
                for(int i = 0; i < projectFound; i++)
                {
                    project = (TCComponentProject)componentOfElements[i];
                    projectlist[i] = project.toString();
                }
            }
        }
        } catch (TCException e) {
            e.printStackTrace();
        }

    return projectlist;
}
```

Fig. 9. Sample code for getting project information from Teamcenter Application

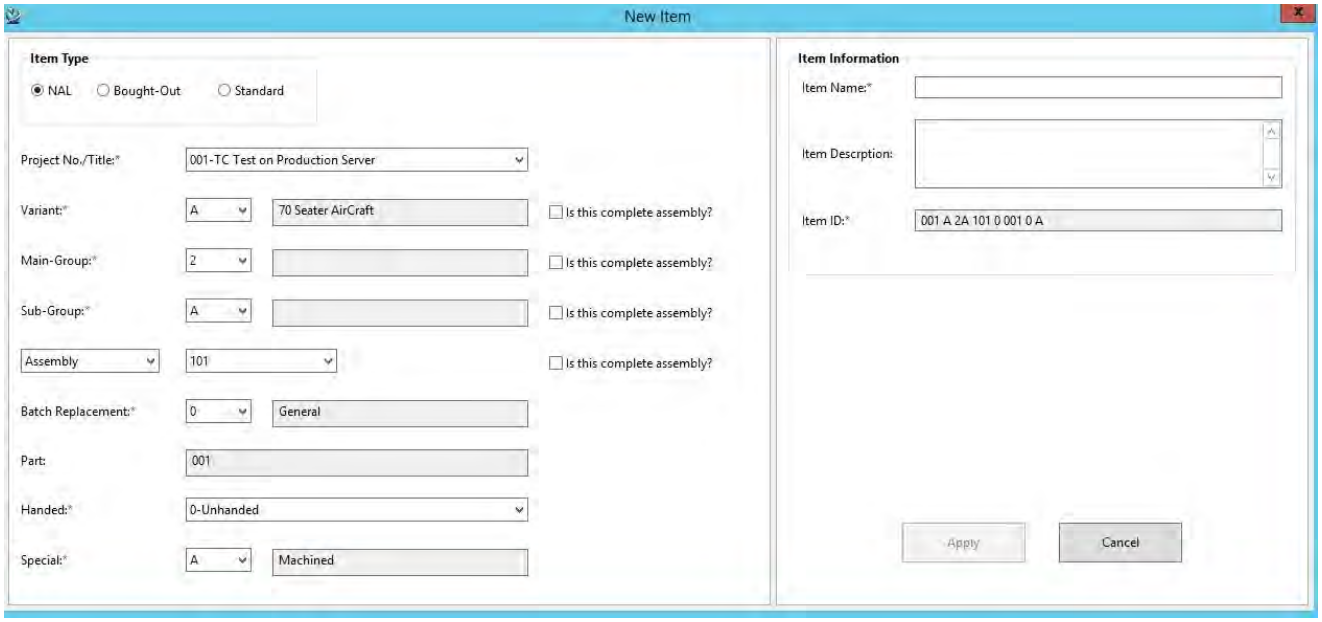


Fig. 10. User interface layout shows populating project information from Teamcenter Application

```
processTitleCombo.addSelectionListener(new SelectionAdapter() {
    public void widgetSelected(SelectionEvent e) {

        String [] lovNameList = processTitleCombo.getText().split("-");

        String lovName = "C4_".concat(lovNameList[0]);

        String[] processAttributeList = new ItemQuery().getlov(lovName);

        processAttributeCombo.setItems(processAttributeList);
    }
});
```

Fig. 11. Sample code for listeners

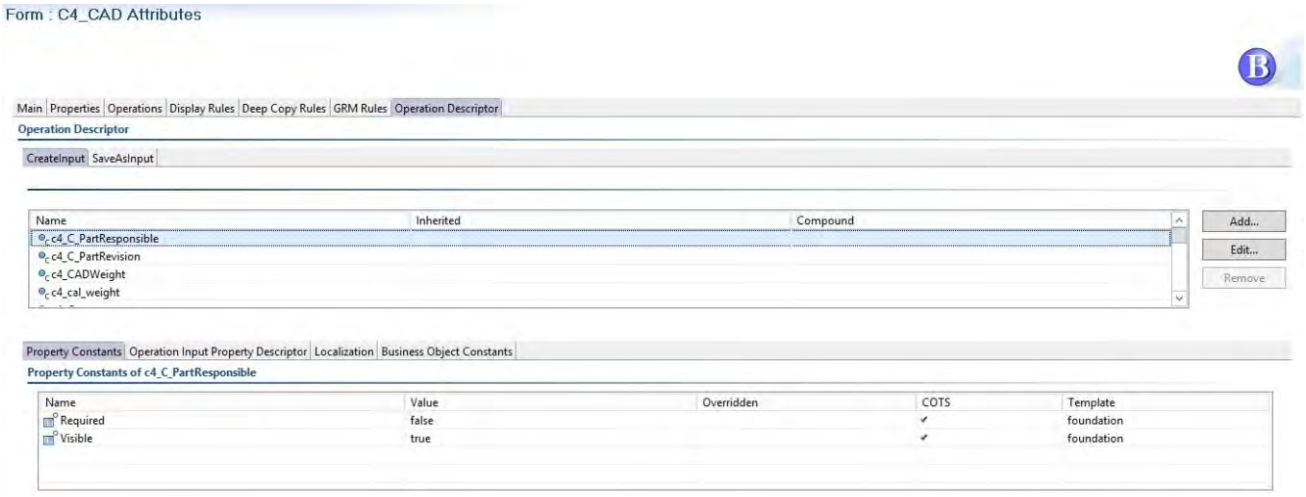


Fig. 12. CAD part general attribute form definition in BMIDE

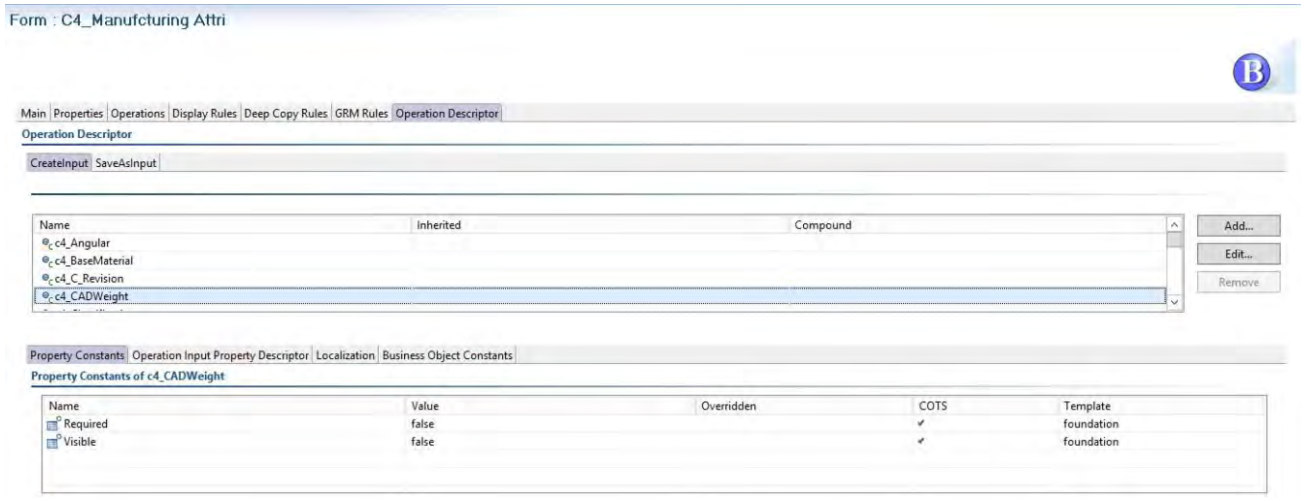


Fig. 13. CAD part manufacturing attribute form definition in BMIDE

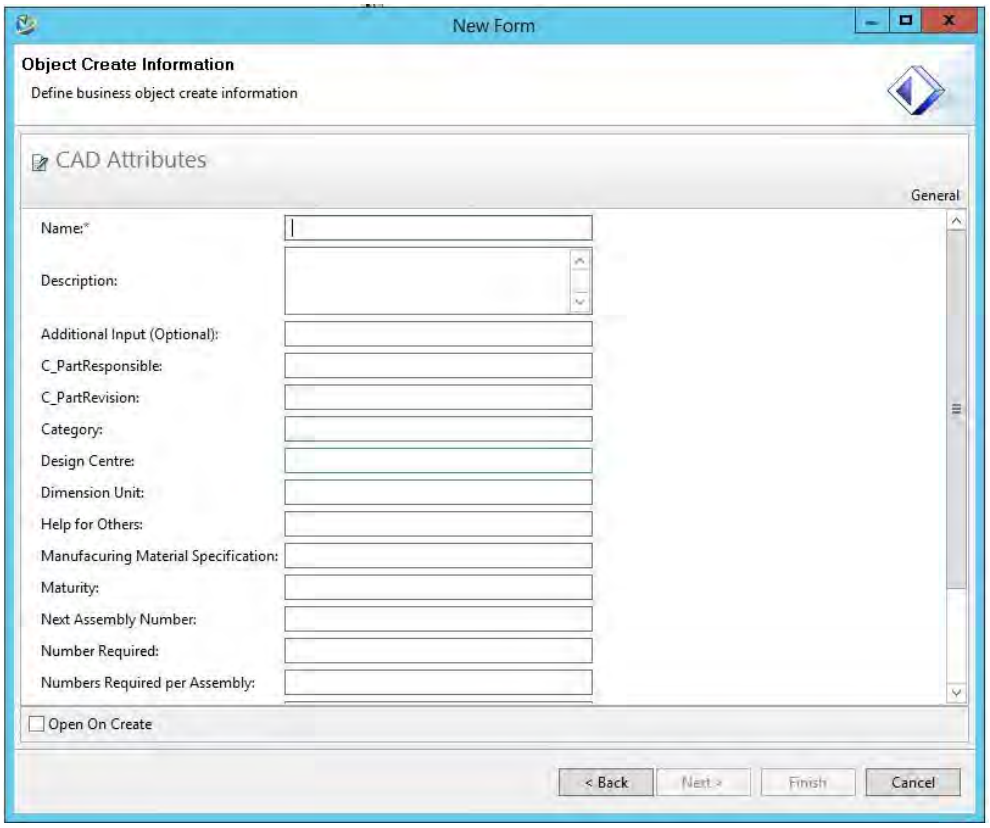


Fig. 14. CAD part general attribute form in Teamcenterz

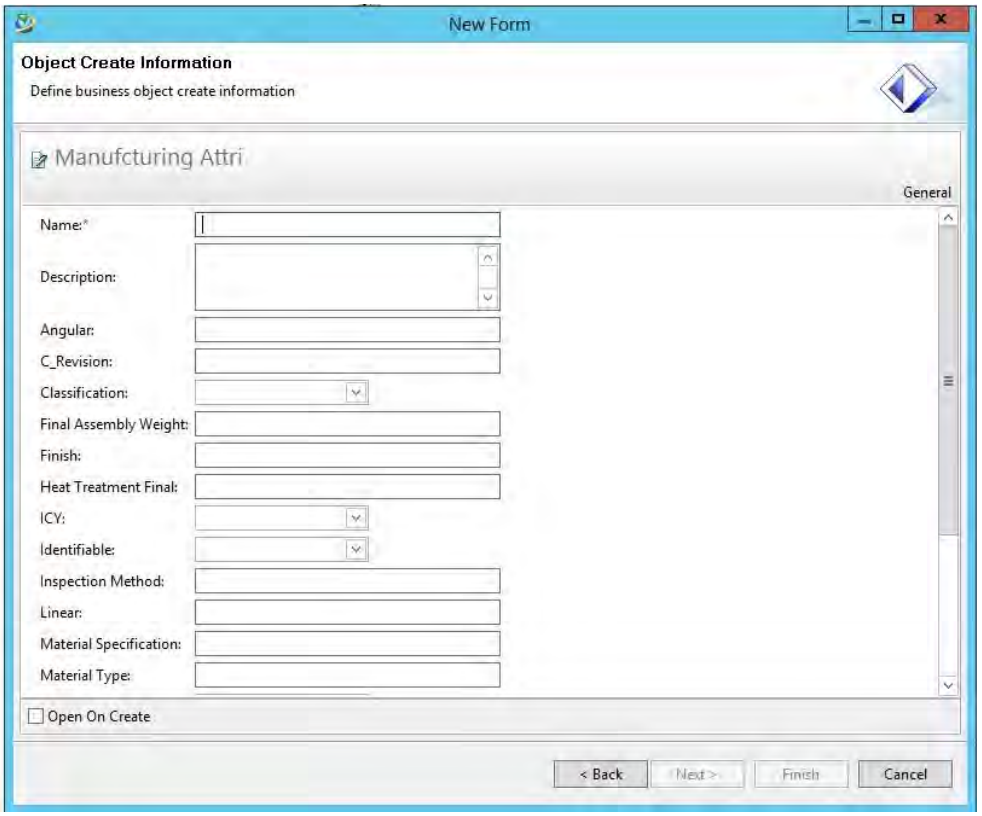
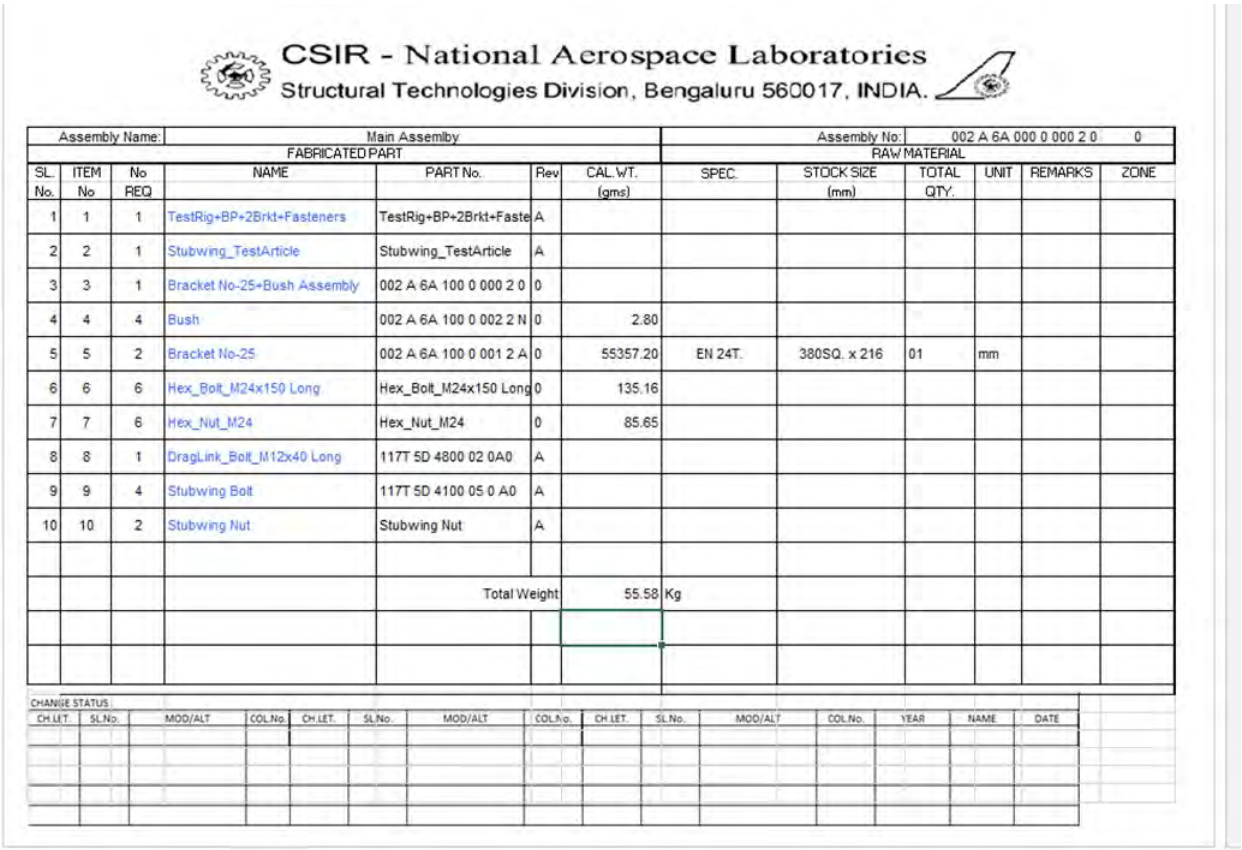


Fig. 15. CAD part manufacturing attribute form in Teamcenter



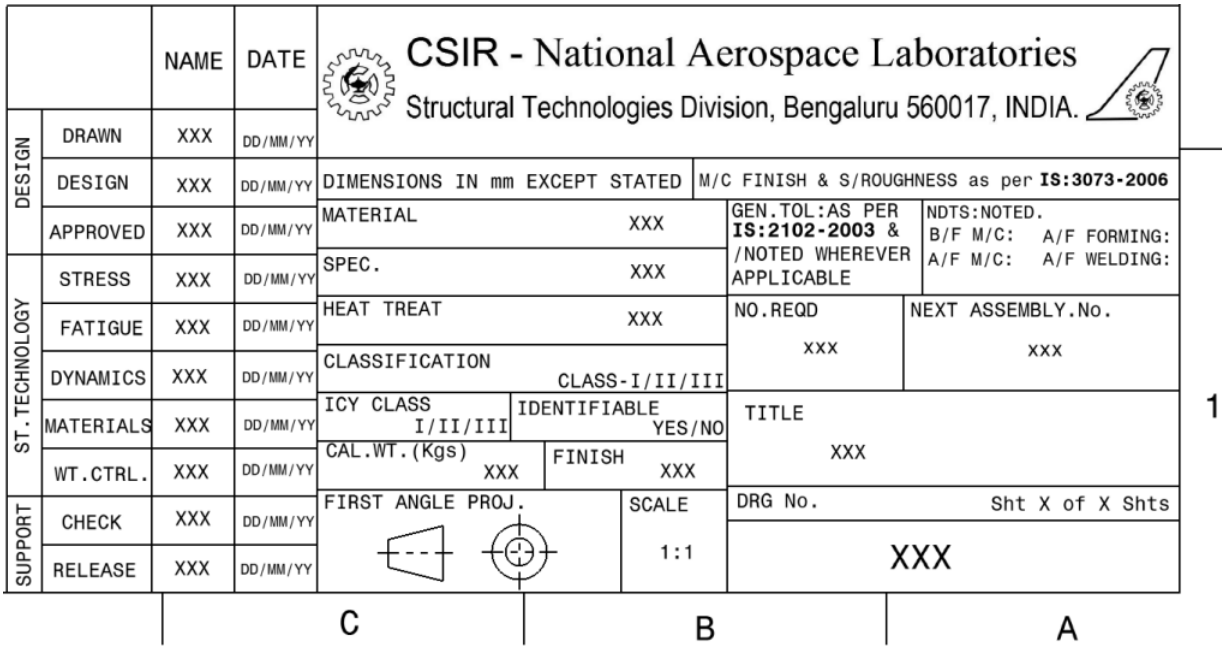
CSIR - National Aerospace Laboratories
Structural Technologies Division, Bengaluru 560017, INDIA.

Assembly Name:	Main Assembly						Assembly No:	002 A 6A 000 0 000 2 0				0
	FABRICATED PART						RAW MATERIAL					
SL. No.	ITEM No	No REQ	NAME	PART No.	Rev	CAL.WT. (gms)	SPEC.	STOCK SIZE (mm)	TOTAL QTY.	UNIT	REMARKS	ZONE
1	1	1	TestRig+BP+2Brkt+Fasteners	TestRig+BP+2Brkt+Faste	A							
2	2	1	Stubwing_TestArticle	Stubwing_TestArticle	A							
3	3	1	Bracket No-25+Bush Assembly	002 A 6A 100 0 000 2 0	0							
4	4	4	Bush	002 A 6A 100 0 002 2 N	0	2.80						
5	5	2	Bracket No-25	002 A 6A 100 0 001 2 A	0	55357.20	EN 24T.	380SQ. x 216	01	mm		
6	6	6	Hex_Bolt_M24x150 Long	Hex_Bolt_M24x150 Long	0	135.16						
7	7	6	Hex_Nut_M24	Hex_Nut_M24	0	85.65						
8	8	1	DragLink_Bolt_M12x40 Long	117T 5D 4800 02 0A0	A							
9	9	4	Stubwing Bolt	117T 5D 4100 05 0 A0	A							
10	10	2	Stubwing Nut	Stubwing Nut	A							
				Total Weight		55.58 Kg						

CHANGE STATUS

CH.LET.	SL.No.	MOD/ALT	COL.No.	CH.LET.	SL.No.	MOD/ALT	COL.No.	CH.LET.	SL.No.	MOD/ALT	COL.No.	YEAR	NAME	DATE

Fig. 16. Typical EBOM template



		NAME	DATE	CSIR - National Aerospace Laboratories Structural Technologies Division, Bengaluru 560017, INDIA.	
DESIGN	DRAWN	XXX	DD/MM/YY		
	DESIGN	XXX	DD/MM/YY	DIMENSIONS IN mm EXCEPT STATED	M/C FINISH & S/ROUGHNESS as per **IS:3073-2006**
	APPROVED	XXX	DD/MM/YY	MATERIAL XXX	GEN.TOL:AS PER **IS:2102-2003** & /NOTED WHEREVER APPLICABLE NDTS:NOTED. B/F M/C: A/F FORMING: A/F M/C: A/F WELDING:
ST.TECHNOLOGY	STRESS	XXX	DD/MM/YY	SPEC. XXX	
	FATIGUE	XXX	DD/MM/YY	HEAT TREAT XXX	NO.REQD XXX NEXT ASSEMBLY.No. XXX
	DYNAMICS	XXX	DD/MM/YY	CLASSIFICATION CLASS-I/II/III	
	MATERIALS	XXX	DD/MM/YY	ICY CLASS I/II/III IDENTIFIABLE YES/NO	TITLE XXX
	WT.CTRL.	XXX	DD/MM/YY	CAL.WT.(Kgs) XXX FINISH XXX	
SUPPORT	CHECK	XXX	DD/MM/YY	FIRST ANGLE PROJ.	SCALE 1:1 DRG No. Sht X of X Shts XXX
	RELEASE	XXX	DD/MM/YY		

C B A

1

Fig. 17. Typical drawing title block

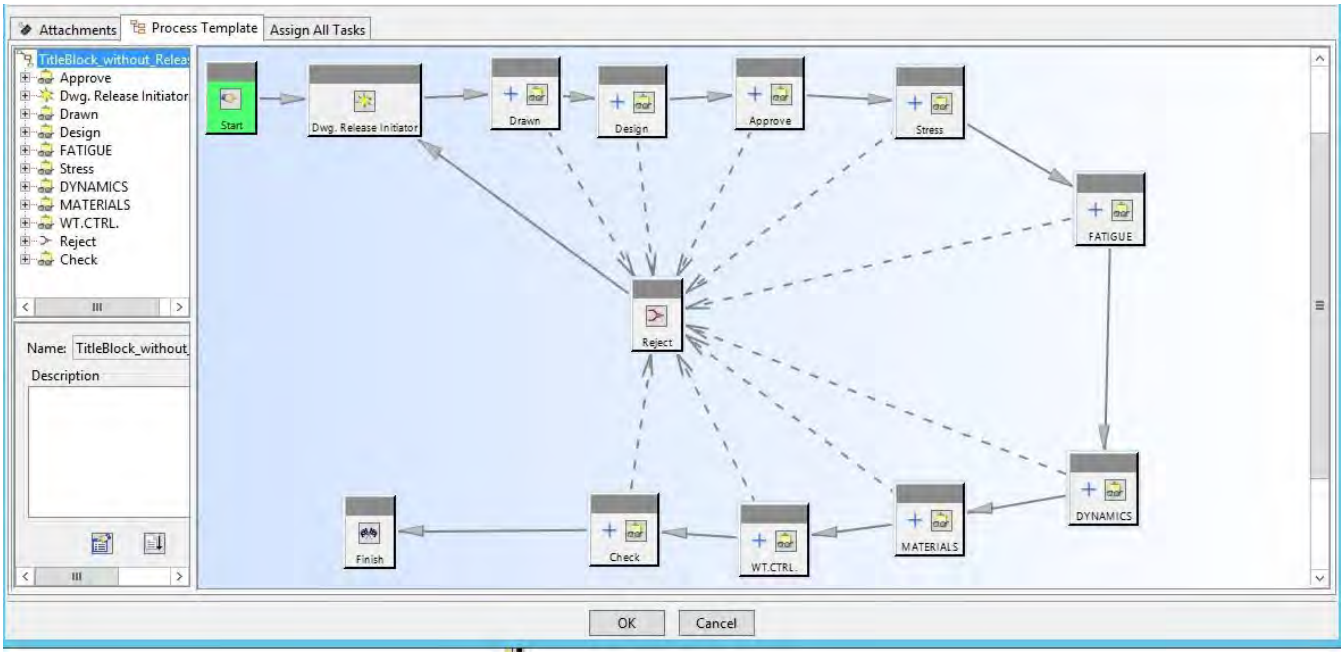


Fig 18: Typical workflow approval process

CONCUSION

Considering the best practices, proposed and implemented a unique numbering system for the CAD parts/assemblies, standard templates for the drawing title block and engineering bill of material, etc. through configuration and customization of 'Teamcenter' application as part of the in-house development of Design and Simulation Lifecycle Management (DSLM) system at the division. This helps in reducing the product design cycle time and enables the organization to deliver the product in shorter time at a competitive cost.

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Reimagining product structure for Modular Build of a Fighter Aircraft

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Abstract - Advanced military aircrafts are the most complex machines wherein state of the art avionics and other LRUs are integrated onto completed Airframe. This sequential build of airframe followed by equipping is a time-consuming process. Modularization of primary structure with concurrent integration of equipment is being employed to reduce jig cycle time and to improve build rates. This poses various challenges regarding management of data in product structure. In this paper, a novel approach to manage product structure of entire aircraft in a modular build scenario in a PLM environment is presented. The complete framework of modular product structure and its representation in PLM software is presented. This novel product structure addresses management of both conventional product structure as well as modular product structure. Also, product structure is designed to address the issues about configuration management.

Keywords - Product structure, Modular Build, Equipping, Jig cycle time, Build rate, Configuration management

I. INTRODUCTION

Advance military fighter aircrafts are one of the most complex systems in the world. These fighter aircrafts are in a way combination of Structure consisting of Fuselage, Wing and various systems like Flight controls, Electrical & Avionics system, Environment control system, Fuel system, Hydraulics etc. Conventionally, aircrafts are built sequentially i.e., the major structural elements are built and then coupling of all structural elements is completed followed by installation of various systems. This approach results in longer build times and reduced build rates.

1.1 Modular build

Modular Build in aircraft production is one way of achieving reduction in build times and thereby improving the build rates. It is evidenced that modularity reduces development and manufacturing lead time in aeronautical industry[1].In modular build approach, the structural elements are further divided into various sub modules and these are concurrently built.The basic theme of modularization is to shift as much of assembly activities as possible to the upstream stages of sub-assembly and make a assembly module at the earliest opportunity in the build.Since modular build shift assembly operation upstream, the quantum of assembly work gets distributed among various stages of the build and evens out the cycle time. This aspect sets up 'Assembly Flow' and is handy for achieving critical times and establishing assembly line balancing.The final assembly jigs becomes simple

in design & construction, as it receives few subassembly modules rather than huge number of loose detail parts.Final assembly jigs will be open in construction and this facilitates effective ergonomics, leading to easy & quick loading of parts & assemblies. It also ensures easy unloading of completed structural assembly modules. As effective & extensive Key characteristics (KCs) can be defined & implemented for structural modules ,Inspection becomes a progressive activity and final inspection time is minimized.Modularizing the design and arranging for product variants to be produced as late in the assembly sequence as possible enables controlled variation and aids just-in-time (JIT) production. Modular build facilitates effective out-sourcing of modules which increases build rate.

In addition to this, the equipping is done the in the modular build level itself resulting in stuffed modules. These stuffed modules are then coupled together to complete aircraft build. Design facilitates this modular equipping by providing break connectors for looms, unions for hydraulic lines & suitable connectors for control rods / cables.-Modular equipping creates opportunity for out-sourcing of equipped structural modules. The out-sourcing content can thereby be substantially increased. Modular equipping evens out equipping activities among the modules, effectively reduces flow time and increases throughput. Additionally, modular equipping facilitates stage inspection and troubleshooting &corrective actions become quick, easy & effective. However certain amount of redundant inspection will be introduced when the final inspection of these systems are carried out. This should only be viewed positively as the additional reliability built into these systems. It must be reiterated once again that all equipping brackets, will be installed, on or off jig, as part of structural assembly.

Effective modularization of the structure build & equipping is a critical key factor for successful productionization of the aircraft. It facilitates simple, quick and accurate build, which ensures effective utilization of resources, including manpower. It also facilitates change management & configuration control procedures to be simple & effective. However modularization brings with it critical technical challenges of building accurate & identical assembly jigs and manufacture of accurate detail parts.

1.2 Product structure

The product structure is hierarchical representation of parts, subassemblies, and assemblies. According to Peltonen, product structure explains the fact how the product is divided into components, which are in turn divided into subcomponents [2].The product structure generally consists of installations, assemblies, sub assemblies and parts with clearly defined relations between them The product structure represents the sequence in which the build is accomplished.

Product structure is used to generate the bill of materials(BOM) for a build.

Product structure is built in the initial design and development phase.Proper configuration of the product structure into sub-assemblies allows division of design tasks and teams, and the accumulation of specific expertise.

The product structure is built and managed in a PLM package .Each detailed part or assembly is represented as a product structure item in PLM , complete with part number and part description. The item modifications section contains detailed information regarding parts, such as 3D models and meta data. PLM provides for the release of item revisions and the control of change to an item revision. After the release of the most recent revision, if a portion needs updating, the item is revised once again, and the new revision is updated in accordance with the updated requirements.

Product structure also controls product's adaptability necessary to respond to changes in customer requirements and various product structures are built over the lifecycle of the aircraft .

2. Analysis

2.1 The need for Modular build

There is a continuous demand to increase the production rate of Light combat aircraft to meet the delivery targets. One way to achieve this is to increase the number of production lines. But increase of production lines, is an investment intensive process which require huge investments also and take considerable amount of time in setting up.

Another way to ramp up production rate is to reduce the overall build cycle time. This is achieved by building the aircraft concurrently. Modular build is the process of dividing the fuselage and wing structures into various sub modules which are then built concurrently and are assembled. In addition to modularizing the Fuselage structure, system brackets installation and limited equipping is also completed at the module level which in turn reduces the equipping time leading overall reduction in build time.

In this paper the study of modularizing the fuselage structure is analyzed along with the representation of modular build in PLM product structure. Also, the various issues arising out of the modular build implementation in PLM build and how these are resolved are also presented.

The aspects considered for modularization in Fuselage for a fighter aircraft are listed below

- Feasibility of Design layout with optimum modules for reducing jig cycle time at module levels -Optimized split of various structural elements to form various modules based on functional and access requirements.
- Assessment by System groups & definition of bracketry installation requirements at each module level to optimize build time.
- Defining assembly sequence and related details in modules
- DFMA approach at each module level (to incorporate jigless tooling to the extent feasible)
- Study and provision of Design features/tooling for Material Handling of modules
- Defining Additional tooling requirements to enable seamless mating of modules
- Defining inspection stages at critical joints after module mating during build to ensure design intent.

3. Conventional Build product structure

In conventional build product structure, there is a clear distinction between the structure and the system elements and is very easy to represent.

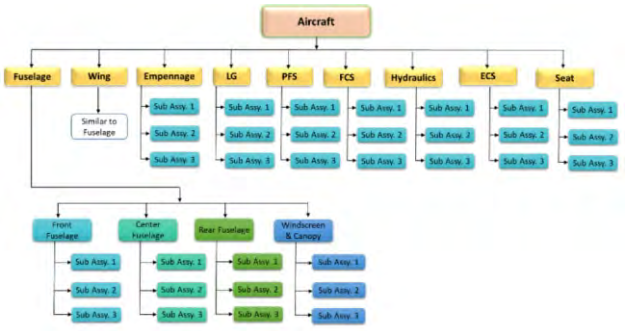


Figure 1: Conventional Product Structure

4. Modularizing of Fuselage

In fighter aircraft, the fuselage is divided into Front, Center and Rear Fuselage portions. These major assemblies are divided into modules. The typical modules of are as shown below. The front fuselage is modularized into 5 modules, center fuselage into 9 modules and rear fuselage into 4 modules.

4.1 Numbering of Modules

After modularizing each module is identified with a unique numbering system and the numbering of system brackets and equipping coming in a particular module is assigned with a specific number.

5. Modular Product structure

The below picture explains the way modular product structure is arranged.

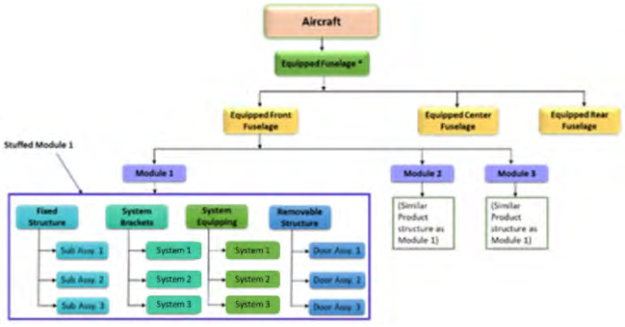


Figure 2: Modular Product Structure

Every module in modular build is consists of essentially 4 different assemblies

a. Primary structure
b. System brackets coming in that module
c. Equipping coming in the module
d. Removable portion in the module (Doors & Covers)

The module with all the 4 elements is termed as "Stuffed module".

In accordance with each of the modules all the system groups are then required to modularize their respective systems. The below mentioned groups are required segregate their bracketry and locate in the module

a. Electrical and Avionics
b. Hydraulics
c. Flight controls system
d. Environmental control system
e. Power plant and fuel system

The modular product structure poses various challenges as the structure and systems are contained in the same assembly node. The modular product structure posed the below mentioned challenges.

a. Handling of data related to systems
b. Configuration Management
c. Change Management
d. BOM Management

5.1 Advantages of Modular build product structure

a. Each of module contains all the system brackets and equipping details in the module level itself
b. Since all the system brackets are installed during module level, access for installation is much better
c. Any testing to be carried out such as "leak check" can happen at the module level itself and certified modules can be sent for coupling.
d. As removable portion also is installed in the module level better control of Interchangeability is possible.
e. As all the system related brackets are installed in the module level, equipping time is greatly reduced.
f. The difference between Design BOM and manufacturing BOM is almost negligible.

6. Challenges in Modular Product structure

6.1 Handling of data related to systems

In the modular build product structure, the systems data is spread across various modules of structure. If any system is to be loaded completely for visualization, it is essential to load all the parts of the system from every module.

To address this aspect, system level handles are provided at all levels. These system handles will enable selection of a particular system for visualization across modules.

6.2 Configuration management

Configuration Management (CM) is the process of handling products, facilities, and processes by managing the information about them, including changes, and ensuring they are what they are supposed to be in every case. [3]

In the customization of PLM for modular build, handlers are provided to address tail number wise configuration.

Also, there is provision to define various configuration management handles available wand also can be customized.

6.3 Change Management

The objective of the change management is to accurately update the product structure with the changes to capture the complete change impact at the same time limiting changes only to level which is necessary.

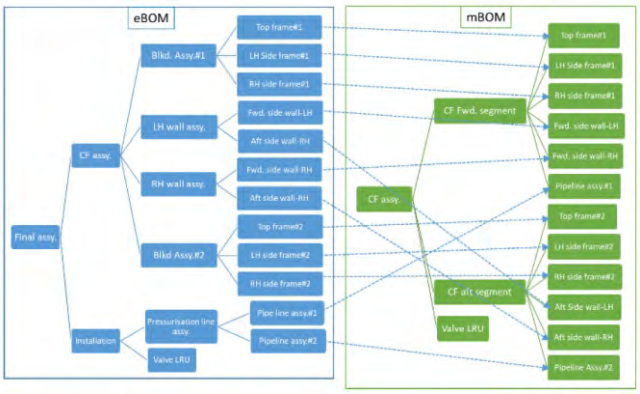
Change management becomes very critical in modular build scenario as system and structure are represented in a module. Any change in system or structure will result in bubbling up and thereby increasing the work. To address this issue, config nodes are introduced at every level which will take care of bubbling up issue.

6.4 BOM Management

BOM management has become the hub of

information integration throughout the product lifecycle. [4] With concept of modularization, EBOM is closer to MBOM thus enabling seamless manufacturing.

The modular build as represented in product structure is close to what is built and the sequence of assembly is properly defined. The below picture explains the difference between eBom mBOM



7.RESULTS AND DISCUSSION

The modular product structure developed enables aircraft build concurrently thereby enabling faster aircraft build and improved build rates. A comparison of the build times with conventional build as opposed to the calculated build times using modular build structure shows an estimated reduction of 50% can be achieved in the build time by the modularization methodology.

8. CONCLUSION

The developed product structure captures structure and effectively. The framework is also designed to accommodate any conventional product structure as well. Configuration management and change management are built into the system. Necessary filters are also developed to address concerns of the system engineers for enabling loading of a particular system completely even though the system is spread across various modules.

Acknowledgement

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PLM for Achieving Connected Products and Sustainability

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Abstract / Executive Summary -

Product Lifecycle Management (PLM) is more than an engineering process, rather its a business activity enabling organizations to achieve the realisation of the products and integrates product portfolio to larger business systems, from concept to obsolescence in a systematic way. Organizing, capturing, and leveraging the product data throughout the lifecycle in a single location; allowing everyone to easily know who owns the data and where they can find it; is a big challenge in most of the organizations for users to successfully perform their jobs while eliminating information silos and unnecessary data chase. The objective of this submission is to provide a synthesis of – (1) Product Life Cycle Management guidelines inline with ARP4754 and ARP5007, (2) Typical issues and challenges with the current practices, (3) Potential developmental work across industries (Lean and agile approaches) to improve the PLM system, (4) Future of the PLM system using advanced digital technologies to enable connected products and (5) Integration of sustainability features in PLM to enable sustainable ecosystem. By leveraging the product lifecycle experience in the industry ecosystem, themes on PLM to enable connected products and sustainability are investigated and presented for the future recommendations.

Keywords -
Connected Products, PLM, Sustainability

I. INTRODUCTION

1.1. PLM Evolution

The evolution of product lifecycle management started with the idea of creating a competitive advantage over heavyweight rivals in the automotive industry without spending too much on parts management and tracking. In the 1980s, its primary objective was to keep track of the part from the inception of the product till the end of its life to enable efficient management of the products' processes and inventories (SAP, 2023). At the end of the '90s, Automatically Programmed Tool (APT) and Computer-Aided Design (CAD) software solutions were integrated with the PLM, and PLM eventually became a critical information generation tool about the products and their parts along with part tracking. Today, PLM has come a long way and is one of the core elements of the digital transformation (Nyffenegger et al., 2018) of engineering processes for original equipment manufacturing (OEM) organizations and, has been projected with enormous potential to enable connected products

1.2. PLM as Engineering Process

Grieves (2005) defines PLM with characteristic and boundaries to propose models that help us conceptualize both holistic and component views in compact packages. Design of complex engineering system such as air vehicles presents complexity and variety of the products, person dependent enterprise becomes inefficient and insufficient hindering the scaling up of the process and growth of the enterprises. This is due to scattered information, disconnected components specifications and time-consuming process of compatibility analysis. These challenges created opportunities for development of simper tools which are user centric, not heavily dependent on the user's memory and efficient in performing calculations.

Organizations started seeing the value PLM brings in the engineering activities in connecting engineering teams, providing needed product authority in designing, evaluating, validating and autho-

rizing the approvals for the designs and reports. PLM has been a secure tool for the configuration management of the product's functional as well as physical configuration. It provides means to implement only the authorized changes and also help suppliers to be part of the products' extended team.

1.3. PLM as Business System

Apart from engineering process the PLM has also been performing business solution in streamlining the flow of information about the product and related processes throughout the product's lifecycle. PLM facilitates the availability of the right information in the right context at the right time. The PLM also supports a company on its value chain and seeks to reintegrate people, processes, resources and information. Terzi et al. (2010) noted that organizations have realized that keeping focus on products and creating a common language around them is more than just a theoretical viewpoint but has seen as fundamental building block to the success. In the digitalization era, requirement of a forward looking PLM is need of the organizations with product development as their competitive advantage. PLM has been adopted across organization to foster collaboration tool to integrate globally distributed teams. By being hub for product and parts information, it has positively impacted the product innovation outcome. Benefits of PLM has been seen by some organizations in designing the products to suit customer demand and customizing products to meet specific needs.

2. PRODUCT LIFE CYCLE

Product lifecycle has been defined as a strategic tool for decision making in the studies of technical innovation (Mas et al., 2021). Literature in PLM has defined that products lifecycle consists of multiple phases based on industry and product context (Stark, 2022). In this paper, we take a case of aircraft as product and its life cycle and system development cycle. Figure 1 exhibits the most used development lifecycle from Aircraft Recommended Practices (ARP) from Society of Automotive Engineers (SAE) International. The development is broadly divided in three phases. Next we discuss each phase and role of PLM processes, tools and capabilities.

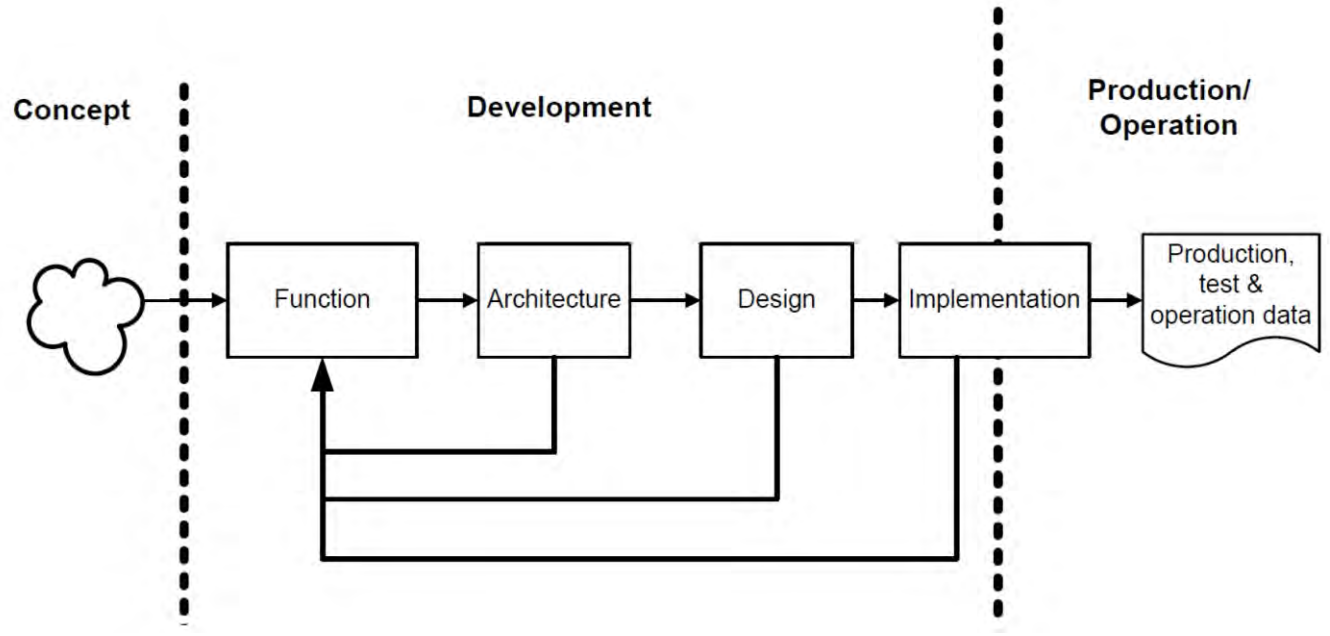

Figure 1. Development Life Cycle (Ref: ARP4754)

The concept phase determines the overall aircraft performance and configuration such as payload and range, aircraft size, number and locations of engines, applications of new technologies in design and manufacturing. During the development phase, which follows the concept phase and, translate overall architecture of the aircraft in lower-level components such as design of the functions and allocates these functions to items. These items are then realized in the production phase and sustained in the operations phase. The initial concept of the product is expected to be integrated in the PLM and functional modules to be translated to product items. The PLM is proposed to consolidate and provide one stop shop for the deliverables and documents from the development phase. These documents are functional build architecture and design data including drawings, models, BOM which helps manufactures to realize the part. This phase also captures traceability of the requirements, their compliances, and limitations, for verification and validation of the product in their later phases. The PLM is a medium to Linkage of the artefacts – Data and documentation to be generated at each stage. At production stage the PLM become information hub on product artefacts and, retrieves needed data for manufacturing, testing and operational needs for the product. In addition to the information hub, PLM acts as gateway for the authorised only changes which might be needed for products' feature improvements, performance improvement, obsolescence addressal or increasing sustainability contents as the regulations and compliances emerges.

3. CONNECTED PRODUCTS

New technologies, such as internet of things (IoT), cloud computing, edge computing, are transforming the way of working for the enterprises and industry as a whole by improving the lifecycle management of their product. It may be argued that Industry 4.0 is outcome of the connectedness of the products. In identification of PLM themes Rivest et al. (2019) have noted connected products in the themes of intelligent products and planning for these products starts from the requirements stage by using use case of products' connectedness to gather voice of customer. The information listed in Table 1 below outlines potential use cases on the connected products and their state of implementation in the PLM. These use cases are envisioned across all the phases of the product lifecycle as noted by Goto et al. (2016). The table presented below corroborates with the key features from the 26 cases presented by the authors on IoT use cases for connected products.

The value creation from the connected product and its integration with PLM lies form the information availability and accessibility. Data quality and authenticity of the source is configuration controlled with pre-defined user access and may be extended to suppliers, customers and other stakeholders. The challenges related to data security, intellectual property rights and confidentiality continue to evolve and may need a tailoring based on type of product and attached data items to them.

To be equipped for IoT, products require intricate systems of software, electrical, and mechanical components. PLM will help companies design products for the IoT in the same ways it always has: by enabling the systematic processes, change control, and workflows required to effectively

Table 1. Connected Product Use Cases Implementation in PLM

Phase	Connected products use case	Implementation in PLM
Requirements	New value-added services	Customer requirements and opportunities
Preliminary Design	Unified key performance Indicators	Products' Quality planning
Detailed Design	Connected product usage analysis	Material and process details
Prototype/ Fabrication	Collaboration with manufactures	Ready to use CAD models
System Integration	Service and Support	Product and Asset Connectivity

collaborate across increasingly diverse and cross-functional teams – including ECAD design, systems engineering, and software development teams to meet the specific needs of IoT-enabled products.

4. SUSTAINABILITY

Although its name would imply that PLM manages data from the entire product lifecycle, it does not in fact manage much of any product data from the operational phase: the longest phase and arguably the most valuable to product development and service. Information about real-world usage, operating conditions, performance, and quality remains largely inaccessible to product development teams and processes – creating an open loop with very little systematic use of operational data to improve the work they do.

If PLM could close this loop by leveraging IoT data captured in real time during the operation of the physical products it creates, the entire product lifecycle would reap the benefits. Product planning and design could leverage value analysis to improve features that customers use most, configure offerings to usage patterns, and redesign parts or systems to save on costs while meeting design requirements.

Engineers could be more quickly apprised of quality escapes through the automatic capture, communication, and analysis of sensor data as soon as a product failure occurs. More complete root cause analysis data would enable faster and more accurate corrective and preventive actions, and a standard set of measurable data related to every product failure would drive an unprecedented ability to trend, understand, and avoid conditions that lead to quality issues. This would benefit service teams, as well, equipping them to monitor fielded products for these trends, initiate proactive measures, and prevent product failures before they occur: improving the user experience while streamlining service delivery.

Model-Based Definition (MBD) refers to 3D CAD models that provide specifications for a component or assembly without additional 2D engineering drawings. These specifications include geometric dimensioning and tolerancing (GD&T), bills of materials (BOMs), technical data packages (TDPs), engineering configurations, design intent, etc. Collectively known as product manufacturing information (PMI), these data sets, their metadata, and their linked repositories contain the information to manufacture and inspect the product. Model-Based Definitions are also known as “digital product definitions.”

5. CURRENT ISSUES AND CHALLENGES

5.1 Inefficient Integrity and Accessibility

To enable PLM to be efficiently integrated with Industry 4.0 technologies, there are multiple issues related to data which needs to be sorted out to enable seamless product work flow.

- Data Location: Multiple data for same part/item stored at multiple locations and not ready for direct reuse.
- Disconnected & Limited data: Data is inconsistent and disconnected in terms of work flow, unit of measure, interface description and other performance / test details. Not able to identify correct data / document type leads to omission of the needed data from the product hierarchy.
- Configuration and Change Management: Most often the Customer oriented changes throughout the life cycle, field failures, non-compliance disposition, Build matrix, Configuration management and BOM updates are the manually dealt processes; which is time consuming, error prone and difficult to manage even for the authorized changes.
- Compatibility: PLM data at current state are not compatible for the purpose of manufacturing and manual export & storage of the drawings and models to share with suppliers.
- Collaboration and knowledge deficit: PLMs in principle presents big collaboration opportunities. However, in absence of simple work flows it also creates deficit of the knowledge transfers hindering true collaboration.
- IP Protection: With the exposure of the PLM to other enterprise tools within organisation and with access to suppliers and customers, the intellectual property protection is a threat.

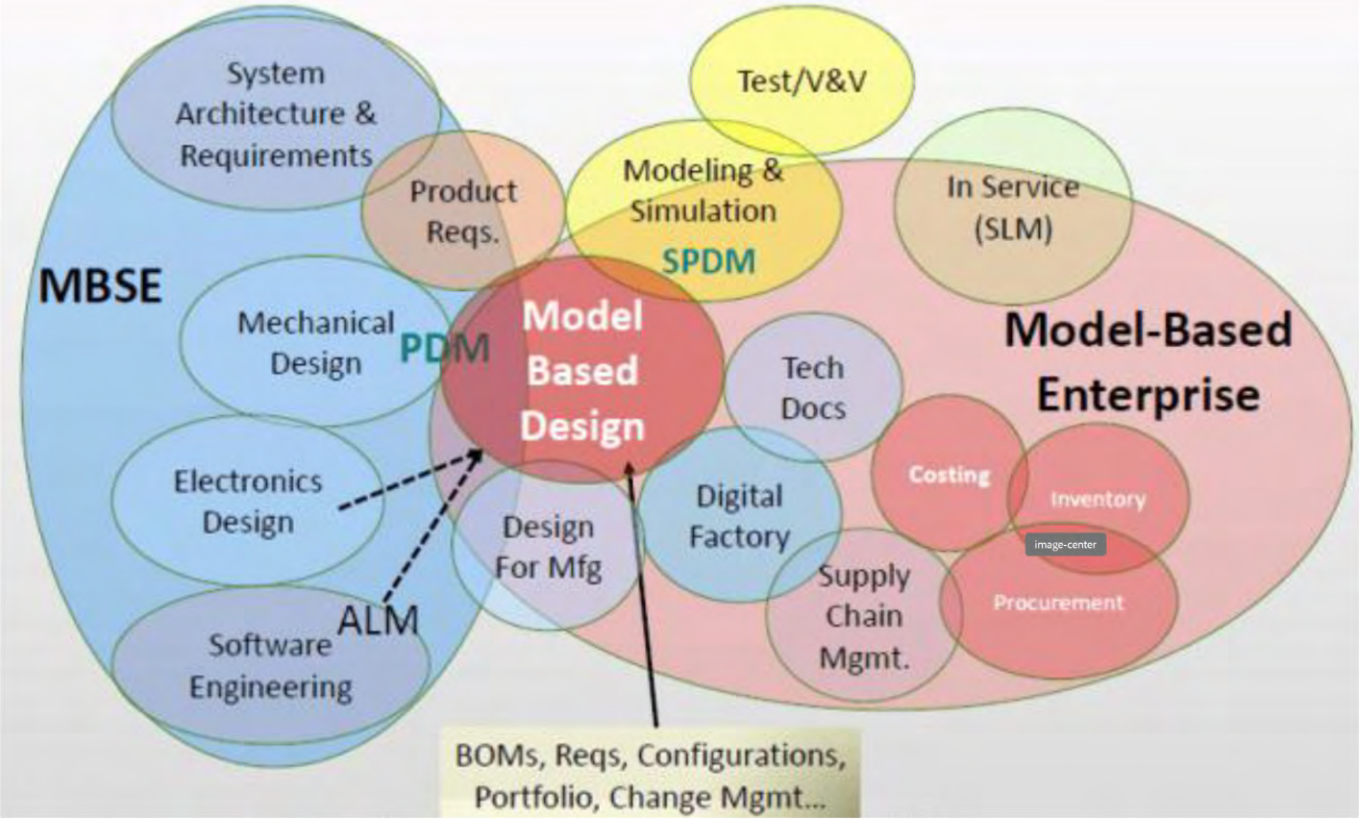

Figure 2. Model Based (MBx) terminologies used by organisations (Source: CIMData.)

5.2 Low uptake on Model Based Approach (MBA)

Systems engineering vision document (INCOSE, 2020) defines Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. It is proposed that once an agreement is reached on model based approach for its integration in the PLM processes, there will be bidirectional communication on the creator of the model/data to the user of it, for instance a design engineers (a creator) to factory (as user). Figure 2 shows the fragmented presence of model based data which is in silos at this moment and to have these integrated in the PLM, additional functionality such as more data types, more user type, stricter change control will be needed. Once this capability level from the processes and tools perspective and maturity on MBA level is achieved, capabilities will become widely available across the enterprise and to the extended enterprise of partners, suppliers, and customers.

5.3 Lack of integration of Advance Technologies

PLM offers designers and engineers a deeper level of insight into product requirements. Ingesting data from many different internal and external sources, a PLM system with integrated machine learning can turn performance data and customer feedback into new feature suggestions.

If we take functional level development of fly-by-wire actuation system (ARP 5007) as an example to see current engagement of the PLM in aiding and housing the deliverables during its various phases as listed in Table 2. The development cycle is covered in multiple developmental phases and completion of each phase is dependent on creational, submittal and approval of multiple deliverables of each phase. The table highlights the PLM tools are engaged only during the middle of the product development and has a lot of potential to get engaged during other phases.

Table 2. Engagement of PLM in Design Phases of a Function in Aircraft

Product Design Phases	Primary Deliverables	Leading to Milestone	PLM engaged?	Potential for Future
Requirement analysis	System configuration (Hardware, Electronics, Software). Architecture, interface, Geometry, Power, initial sizing, failure detection, maintenance planning, etc.	SRR (System Requirement Review)	Rarely	Integration of MBSE (Model based System Engineering)
Preliminary Design	Preliminary design synthesis Trade-studies and design studies results Functional flow, requirements allocation Layout drawings Environmental and thermal design Preliminary parts list Preliminary weight analysis Risk mitigation items	PDR (Preliminary Design Review)	Very often	Integration of MBD (Model Based Design)
Detailed Design	Design Analysis Design Studies Results Assembly and Detail Engineering Drawings Performance Analysis Parts List Weight Analysis Interface Control Drawings Materials and Processes Design-to-Cost Analysis	CDR (Critical Design Review)	Often	Integration of MBD/MBE (Model Based Design/ Engineering), Life Cycle Assessment Tools towards sustainability
Development/ Fabrication	Design changes Test plans & procedures Test facility and resource requirements Instrumentation/data system capabilities and calibration requirements Review of automated test procedures	TRR (Test Readiness Review)	Rarely	Integration of MBE (Model based Enterprise), Use of IoT
System Integration	Functional Configuration	FCA	Often	Integration of MBSE & Digital Twins, Use of IoT
	Physical Configuration	PCA	Rarely	

6. INTEGRATION OF TECHNOLOGIES - FUTURE OF PLM

The future of PLM is defined in Figure 3 and are further elaborated in Paragraphs 6.1 to 6.3.

6.1. Connected Products & Portfolio

In the era of internet of things (IoT) where more and more products are coming in the close proximity to each other and providing controls to the consumer, the connectedness is creating big opportunity to designers, manufacturers to create value to the users of the systems or vehicles. This opportunity can be capitalized using the PLM with the physical, functional, or operational compatibility of the products or items. To realize this, PLM must be equipped with new capabilities and integrated with new technologies that will help it better to develop, manage, and deliver the data and information bidirectionally with the product. On one direction, existing PLM technologies must be equipped to bring ECAD, model based systems engineering, and software into its purview. And on the other hand, to better manage smart, connected products throughout their complete lifecycle, including operation, PLM technology must be closely integrated with the IoT platform technologies and big data analytics that connect to and process data returning from the products which are enabled with IoT compatible sensors.

6.2. Sustainability & LCA Provisioning

From the trade-off studies till the manufacturing

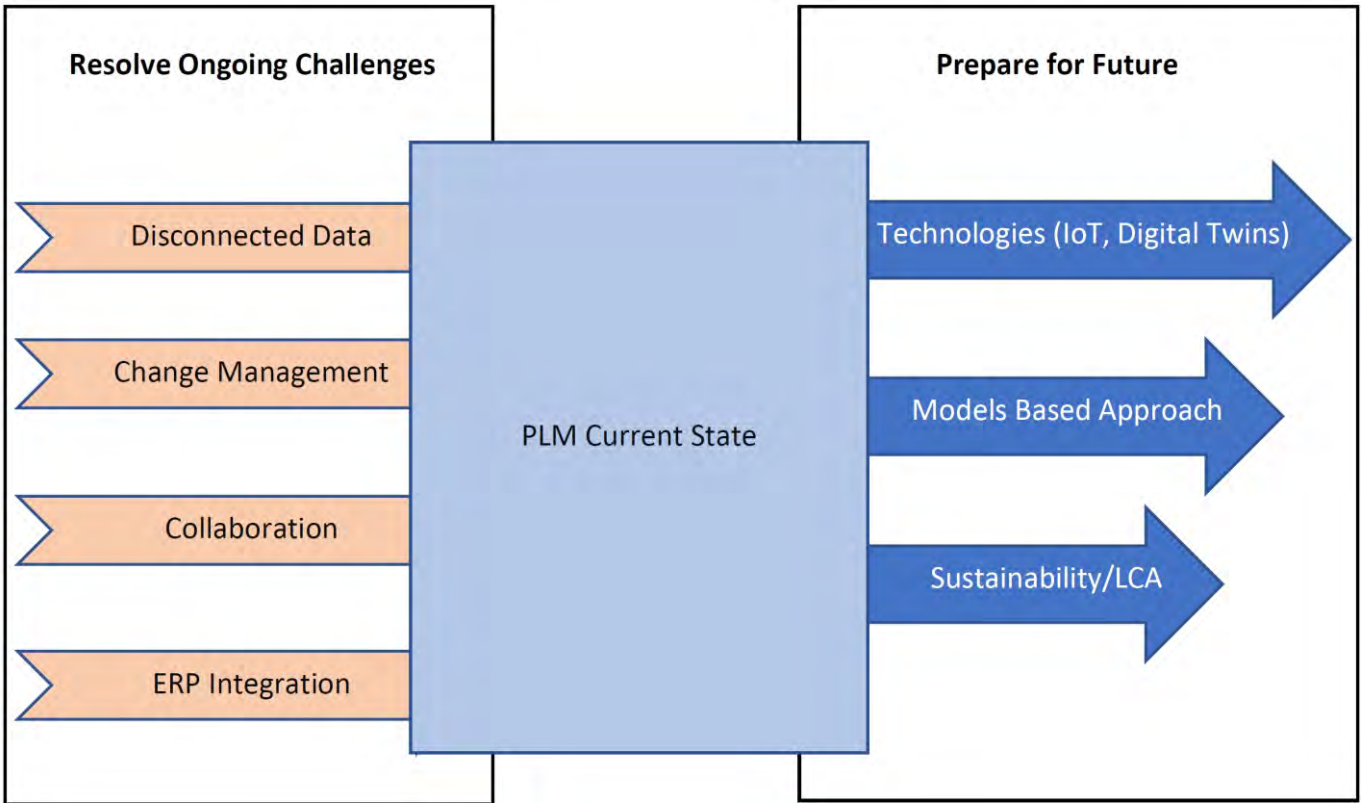

Figure 3. Future of PLM - Transformation Priorities

of the products PLM may provide sustainability provisioning to enable designers with the library of sustainable parts and products to choose from. PLM may thus become information hub on aggregating sustainability related information from each of the stage of the product design to support organisation's reporting needs. 3D CAD models from Model-Based Definition (MBD) may provide specifications for a component or assembly without additional 2D engineering drawings. These specifications collectively known as product manufacturing information (PMI), these data sets, their metadata, and their linked repositories contain the information to design, manufacture, test and inspect the product and also provided predicted useful lifespan based on various environmental conditions. The information related to impact on the environment in term of material and energy usage, reduces operation, maintenance and assembly time are the key indicators which PLM can enable designers to encourage putting thoughts into till it becomes norm.

Another step which can take PLM to great leap in enabling sustainability reporting is integration of life cycle assessment (LCA) tools. Imagine a product which during the design phase has created mathematical model to predict consumption of natural resources, generation of waste and reuse, repurpose towards its end of life. During its operational life, if this is coupled with IoT enabled sensors and other operational data, the future of the PLM will assist prediction events, maturing models for MBSE and create immense value to enterprises, industry and collectively to the future societies.

6.3. Model Based Approach and Digital Twin

Model Based Approach help developing the shared system model fully encompasses the design of the system. Model based approach is a key to acquiring early insights into system performance and technical risks and used as a single authoritative source of truth about the system over its life cycle. The digital thread can facilitate upstream and downstream transfer of knowledge from one program to another. By exploiting

simulation-based modelling and data analytics, the model based approach can help quantify margins and uncertainties in cost and performance.

Digital twins are estimated to reduce Product lifecycle cost when connected with PLM with its physical twin. Our understanding corroborates with Donoghue et al. (2018) that with the use of IoT and machine learning these digital twins will predict the behaviours of the product and systems for their maintenance needs. PLM will be able to easily inform which part need to be ordered and if shared with suppliers, it will provide seamless flow of the material – reducing inventory cost, reducing downtime and efficient management of the resources.

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An Efficient Change Management Processes for the enterprises to realize Design Anywhere, Manufacture Anywhere.

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Abstract - In the current competitive landscape, companies strive to improve the quality and performance of their products continually. Engineering Changes (ECs) play a vital role in incorporating client solicitations and enhancing product features even after their market release. To effectively manage ECs, understanding the interdependencies between various components within a product is essential, requiring multidisciplinary knowledge. This paper focuses on optimizing the Change Management process throughout different stages of Product Development (PD).

The causes of changes can range from customer specification updates to translation faults and challenges in parts creation or fabrication. Unstructured change management policies may lead to information loss concerning the product, emphasizing the need to investigate the change's impact and update related documentation. However, in worst-case scenarios, poorly managed ECs may necessitate production halts and product recalls, underscoring the significance of a well-designed process to prevent errors and mitigate potential losses. An efficient EC process not only ensures swift responses to customer requests but also fosters improved customer relations. This paper highlights the importance of structured Change Management to proactively address product modifications, enabling organizations to stay ahead of competitors and maintain product excellence. By implementing a robust EC process, companies can effectively manage change, improve product development, and strengthen customer satisfaction.

Keywords - Engineering Change Management, Product Development, Product Lifecycle Management

I. INTRODUCTION

Engineering Changes (ECs) are essential for incorporating customer requests and improving products even after their release to the market. An EC refers to an alteration in the approved configuration of a product-related item. The competitive landscape compels companies to continuously enhance the quality and performance of their products, involving customers more closely in the processes can take various forms, affecting dimensions, fits, forms, functions, and materials of products or their components. These changes may be aimed at addressing previously undetected issues, enhancing product functionality and value, or improving performance and efficiency. Effective management of ECs is critical to avoid negative impacts on a corporation's performance, including unnecessary expenses, production delays, and slow market feedback. One key challenge in EC management is identifying how changes in one component affect others, whether through direct or indirect dependencies. Such complexity requires multidisciplinary knowledge to ensure comprehensive identification of all component dependencies. To streamline the process, involving experts from different disciplines during the design phase can facilitate the identification of affected components. Automating the documentation of dependencies in a retrievable format can further enhance efficiency.

When making significant design decisions, controlled modification of product data is crucial. Investigating the impact of changes and modifying all relevant documents is essential. In the best-case scenario, only a few documents require changes, but the worst-case scenario may involve production halts and product recalls, resulting in substantial prestige loss for the company. As the industry trends towards digital product and production verification using virtual reality and digital mock-up technology, effective product data management becomes imperative to handle the increasing number of digital files and corresponding documentation. Properly planned and managed ECs offer a significant advantage to organizations, allowing them to match and even surpass competitors' technological innovations, thus maintaining a competitive edge.

An important issue in managing an EC is to identify how other components are affected by the EC. The dependencies of different components of a given product may be direct or indirect with respect to an EC. When a component is affected by a change in another component that is directly caused by the EC, the dependency is called direct [3]. Dependency relationships can become too complex to be handled by a person with a single technical perspective. It requires multidisciplinary knowledge to ensure the identification of all the dependencies between the components of the product. To document all the necessary dependencies, many people from different disciplines should be involved from the design phase. Such an involvement makes the identification of affected components complete during EC processing. The identification process can be automated by capturing the dependencies in a retrievable format. If a major design decision has been made, the product data must be changed in a controlled fashion. The impact of the change must be investigated, and all documents related to the change have to be identified and modified. In the best case only, some documents must be changed, whereas in the worst scenario is that the production must be stopped and already delivered products have to be recalled with a substantial prestige loss for the company. [4]

When changing approved documents, many companies use a formalized Engineering Change Management (ECM) process where the important issues when making a change are pointed out. The process should be designed to solve the problem and prevent new errors. [5] An EC process that is fast and reliable can even improve customer relations. The trend for the industry is clear with more digital products and production verification using virtual reality and digital mock-up technology. This will surely lead to an increased amount of digital files, which in turn demands secure product data management that can keep track on all virtual and physical products and their corresponding documentation. This impacts on the data management within the EC process, since an increasing number of documents have to be managed and changed. [6]

II. NEW PRODUCT DEVELOPMENT

The New Product Development (NPD) process consists of the activities carried out by firms when developing and launching new products. A new product that is introduced on the market evolves over a sequence of stages, beginning with an initial product concept or idea that is evaluated, developed, tested, and launched in the market.[7]

This sequence of activities as shown in Fig.1 is viewed as a series of information gathering and evaluation of product.

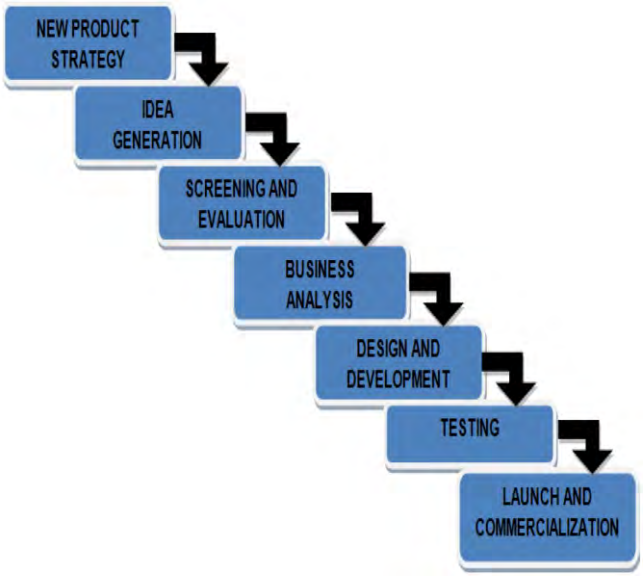

Fig. 1 Stages involved in New ProductDevelopment

The process of information gathering, and evaluation can lead to improved new product decisions on the part of companies by reducing the markets risks/customer acceptance. [8] The NPD process differs from industry to industry and from company to company. Since it differs from company to company, the steps that are followed in most of the companies are defined below to understand the NPD process better. [9]

Different types of testing, i.e., concept testing, prototype/development testing, and test marketing, should be conducted in this stage Product functionality is critical for the testing stage as the aim here is to see whether a product with the attributes called for has been produced. The performance of a product is how well the product achieves the functionality desired. Product performance is usually measured in such ways as testing physical features and functional modes. [10]

For each stage of the NPD process, the factors that are essential for success for each stage is explained in Table 1. The table clearly indicates the desired outcome of each stage, and this outcome leads to gathering of information after each stage where it has to store meticulously for easy retrieval and updating.

Table.1 Desired outcome at each stage of Product Development

Process/Stage	Critical Success Factors
New product strategy	Clear and well communicated strategy
Idea generation	Customer focused idea generation
Screening and business case	Upfront knowledge about the product
Development	Accelerated development
Testing	Product functionality with customer acceptance

A. Accelerated Launch of Product:

Reducing development time is a vital competitive weapon and yields competitive advantage; it means that there is less likelihood that the market or competitive situation has changed by time the product reaches the market and it means a quicker realization of profits. [11]

Companies that develop products quickly gain many advantages over their competitors: premium prices, valuable market information, and leadership reputation with consumers, lower development costs, and accelerated learning.[12] Therefore, the goal of reducing the development time is critical.[13] Most importantly, fast development minimizes the impact of a changing environment.

III. ENGINEERING CHANGE MANAGEMENT

The EC process requires extensive communication between different functions within a company, depending on how far the product is in the life cycle, ranging from design to launch, have been involved. To provide the best solution possible, all involved functions must be able to give their opinion on the change.

This is often accomplished by a cross-functional Engineering Change Committee, which decides upon the change. However, the EC process does not end with the committee decision. The information must be processed several times through the company before the change can be fully introduced. Due to the intensive data management within the EC process, vendors of Product Lifecycle Management (PLM) systems often provide an EC module. [14] These modules assume that the EC process can be generalized and implemented in a computer system as shown in Fig.2

Fig. 2 Simple Change Management Process

The EC process is a core process of the larger Configuration Management (CM) process. Each change of the product or its corresponding documents causes a change of product configuration. This means that every time a new revision of a product document is created, it must be linked to the correct product individuals produced. [15] When a malfunctioning of a product is reported to the company, the corresponding document revisions must be easily found. This is particularly

important in the automotive industry and when many product variants are produced [16]. The implementation of an efficient as well as effective EC process is thus of general importance for a successful Change Management process.

The reason for making changes can originate from different causes. The draft standard ISO11442-6 gives the following examples like change of a part depending on altered function or production requirements, change in the application of a part, introduction of a new part, replacement of a part, correction of errors on a document. The examples above are very much focused on parts and documents. The Change Management with a view that is more focused on different stages in the product development (PD) process would describe the causes as: Changes in the customer specification, Difficulties in parts fabrication or assembly, Quality problems with some subsystem or component, Development for future product revisions.

A. Problem definition and objective

Automotive design and production involve the coordination of activities of thousands of people and hundreds of companies where communication is the biggest importance. With the high increase in computer and networking technology, the automobile industry has strengthened its data management and communication between them significantly. However, disconnect exists among the company's design, engineering, purchasing, manufacturing and service departments.

The disconnect among the departments is due to a lack of communication and an unstructured way of managing the product data. With the lack of structured Change Management policies, the problems that arise are Impact analysis of change management, Lack of communication, Lack of information about the product, Change of data about the product. The above-mentioned drawbacks are due to the unstructured way of Change Management. Therefore, it is always difficult to implement Change Management in an organization.

Engineering Change Management practices intended to divide the design process into manageable stages and ensure the quality at each stage. Organizational structure and size of a firm can influence how a product design change is executed. Many firms have implemented EC procedures to control the impact of engineering design changes. The objective of Engineering Change Management is to minimize the occurrence of changes and if changes occur then handle these changes in a proper way to reduce the loss in terms of cost, time, and quality. With the above-mentioned problem in focus, the main objective of the paper is to structurize the Change Management tool that meets the global standards of Engineering Change Management and to theoretically derive a structured Change Management tool for an automotive industry.

IV. METHODOLOGY

Engineering Change is a highly multidisciplinary domain, and trying to find a general method that supports efficient research in this domain is a task too difficult to incorporate in this work. To structurize the Change Management process in the automotive industry, the basics are to understand the process of design, manufacture, logistics and service in the industry, thus the workflow in the industry has to be studied. The study needs to find the Change Management techniques and tools in practice. The scope for development in Engineering Changes and objectives has to be scrutinized. Based on the existing tools and organizational structure, theoretically derive a strategy to structurize the change management system that can be incorporated in industries.

V. CURRENT TOOLS USED IN AUTOMOTIVE INDUSTRY FOR PRODUCT DEVELOPMENT

Engineering Change Management has to progress through departments like Engineering Design, Simulation, Validation, Purchase, Production and Business Decisions. To support developmental-design activities, it is important to identify the relevant communication channels, as well as the frequencies and contents of communication [17]. From the Study conducted, the Change Request for an item is brought out through Email/Spreadsheets or it has no formalized meth-

odology with regards to conventional Engineering Change Management process. Since it is informal, the history of Change Management and the person who initiated the EC becomes unknown. Change Admittance is a process of approving the Change Request from the business firm or the manufacturing/production firm. Without Change Admittance, further progress in EC is not possible. The Change Admittance in the industry is subjective and is not uniform, in the current EC process. The change admittance is important for the understanding of change severity and the impact of change with other parts of the product.[18] The initial phase of product development includes system definitions like requirements management and conversions of requirements to specifications and proof of concepts [19]. This Phase1 of Engineering Changes is carried out through PLM software. The completion or advancement in the Phase1 process is carried out through email/spreadsheets. This type of advancement will not reveal the involvement of all the team members in the Engineering Change process which leads to the miscommunication between team members eventually lead to the inconsistency in the Engineering Change process.

The Validation and Verification Phase of Engineering Change includes specification, design, Simulation and prototype activities, resulting in a product that meets market needs. The development team iterates designs and specifications based on simulations and prototype results. The Development Phase is complete when all the information required for limited production is matured. Phase 2 in the Engineering Change Request is carried out through PLM software. Communication after the completion of changes happens only through Email/excel sheets maintained in the organization. Since the previous phase happens in PLM System and the intimation/communication happens in this tool will make the team not aware about the parts undergoing the change.

The Business approval process involves the workflow process of a product. The launch of a product is essential for capturing a commercial market than the competitors. [20] The part production approval process in the EC process is carried out through External software. The integration of information from the External software in engineering Change Management is essential since it decides the time to market of the product.

The industry's design and production processes involve the coordination of numerous individuals and companies, emphasizing the utmost importance of effective communication. With the rapid advancements in computer and networking technology, data management and communication within the industry have significantly improved. Despite these advancements, a disconnect persists among various departments, including Design, Engineering, Purchasing, Manufacturing, and Service.

This disconnect can be attributed to inadequate communication and the absence of a structured approach to managing product data. The lack of well-defined Change Management policies gives rise to several challenges, such as impact analysis difficulties, communication gaps, limited product information, and data inconsistencies. These drawbacks stem from the absence of a structured Change Management system, making the implementation of effective Change Management practices challenging within the organization. The current challenges involved in Change Management Process are as follows.

- Details about the Change Initiation are Unknown.
- Information about the Approval and reviewer is unknown in some cases.
- Are all the team members involved?
- Transparency in the parts undergoing change.
- Reliability in Bill of Materials (BOM) update?
- Complication in tracking lifecycle of the product.
- Tracking Priority among Engineering Change.

VI. EFFICIENT CHANGE MANAGEMENT METHODOLOGY

The Engineering Change Management process can vary across organizations, prompting the need for a more comprehensive perspective to ensure

its effectiveness. For an efficient Change Management process in an organization, a systematic flow of work is proposed, outlined as follows:

1 Change Request Initiation: Any user within the
2 when identifying a necessary change. The CR is then processed to move forward in the Change Management process.
3 Change Complexity Assessment: A designated change specialist evaluates the complexity of the proposed change and decides whether it should follow the Full track or Fast track process based on its intricacy.
4 Engineering Change Notice (ECN) Creation: If the change is assigned to the Full track process, Change Specialist 1 generates an Engineering Change Notice (ECN). This ECN is then analyzed by an analyst.
5 Change Review (For Full track processes): In cases where the complexity is high, Change Specialist 1 seeks a review from a Change Review Board (CRB) before proceeding. If approved, an Engineering Change Request for the Full track process is created.
6 Solution Analysis: Change Specialist 2 takes charge of analyzing the change to propose an appropriate solution. An ECN is subsequently created based on the proposed solution.
7 Work Breakdown: The analyst reviews the ECN and breaks down the required work to process and implement the proposed solution effectively.
8 Cross Functional Team Review: The proposed solution undergoes review by a Cross Functional Team. Upon approval, the ECN is officially sanctioned, allowing the implementation process to commence.
9 ECN Implementation: Implementation of the approved ECN triggers two essential processes - the Manufacture Part Approval Process and the Part Implementation Process.
10 Effectivity Application: Change Specialist 3 applies effectivity to the EC, ensuring that the change is implemented at the right time, and ultimately marks the completion of the Change Management process.

By adhering to this systematic flow of work, organizations can facilitate effective Engineering Change Management, leading to smoother coordination, improved decision-making, and successful implementation of changes across departments. There are different States and Status for each stage of the Change Management. The State definitions are. Maturity, Disposition Closure. The State Value definition can be. Elaborating, None, Open, Reviewing, Approved, Executing, Completion, Closed. The Status of EC can be. In-Progress, Design Release, Production Release.

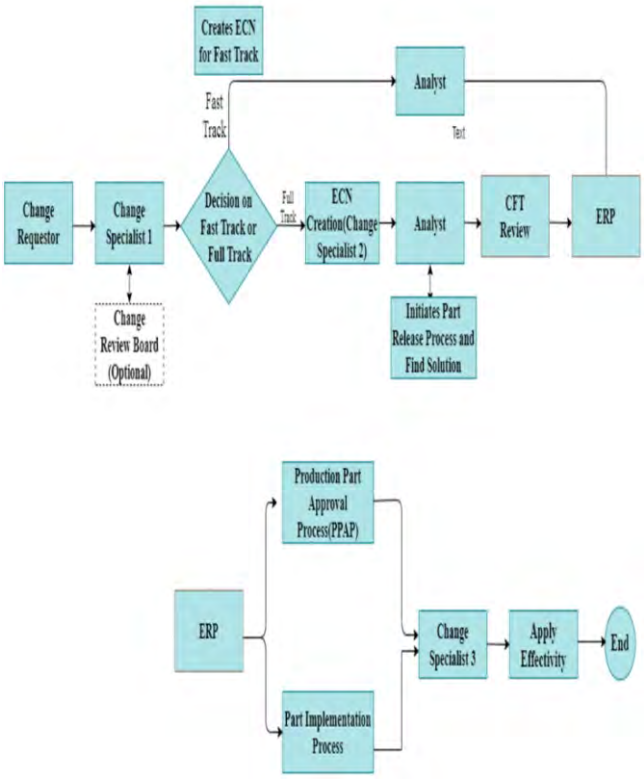

Fig.3 Overview of Efficient Change Management Process

VII. CONCLUSION

In an organization, relying on various standalone tools for Change Management can lead to information loss and increased investments in product development. However, the implementation of an Integrated Change Management System can streamline the process, making it easier to adopt and highly efficient. This integrated system significantly improves product quality, reduces manufacturing costs, and prevents delays in product launches, ultimately contributing to a more competitive product pricing.

For the automotive industry to thrive among competitors, a comprehensive and well-structured Change Management Process is essential. To align with the current trends in automotive development, a broader perspective is established by integrating Change Management within the Product Lifecycle Management (PLM) framework. By digitizing Change Management, human intervention is minimized, resulting in greater efficiency. The proposed model offers a generalized methodology for Engineering Change Management tailored to suit the automotive industry's specific needs. Although capturing dependencies between various components may require substantial effort, the benefits of this highly efficient and reliable approach outweigh the initial investment. Embracing this digitized approach to Change Management holds the key to success in the rapidly evolving automotive landscape.

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Enhancing PLM Concepts for Effective Integration of Design and Manufacturing in the Development of Composite Airframe

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Abstract - Contemporary CAD systems are typically used in product development, encompassing tasks such as conceptual design, layout, detailed design, part models, assembly models, digital mockups, and 2D drawings. These basic elements are essentially associated with Product Lifecycle Management (PLM). In the development of composite parts, the data inputs from CAD, corresponding to manufacturing activities including tooling, processing, assembly, dimensional inspection, and non-destructive evaluation, become significant in addition to the basic elements. These digital data inputs required for each manufacturing activity for a composite component are multifold when compared to their metallic counterparts. Current PLM concepts manage from conceptual design to release of drawings but do not fully capture all lifecycle data, particularly the digital inputs required for manufacturing of composite components. In this work, an effort has been made to integrate the complete lifecycle data related to design and manufacturing during the development of a typical aircraft wing. For the first time, the data inputs for the various downstream activities in composite product development stages have been demonstrated to be attached with the appropriate part and assembly models within the PLM system. This integrated PLM concept is vital for managing data, as it comprehensively encapsulates all the requirements needed in the development of composite airframes, thereby enhancing traceability, reuse, and repeatability.

Keywords - CAD, Product Lifecycle Management, Composite parts, Design and manufacturing.

I. INTRODUCTION

New digital tools and solutions, such as Internet of Things, Virtual Reality, Digital Twins and Simulation, for managing product related data and information across lifecycles, enable new kind of smart product-service systems. Innovative product
development involves a lot of tools, methods, and approaches to create a better product faster. Product lifecycle management (PLM) is one of the tools used in product development to support from inception, through engineering design and manufacturing. Many companies today consider PLM as a core strategic topic. During this period, the scope of PLM and its impact on development

processes has been growing. Today it is understood as a key activity to efficiently manage products and its digital representation through the complete lifecycle. According to Stark, [1] PLM is the business activity of managing, in the most effective way, a company's products all the way across their lifecycles. Sudarsan et al., [2] showed that access, store, serve, and reuse of all the product information throughout the entire lifecycle. Daniels et al., [3] explained the PLM implementation in multiple sectors from electronics, healthcare, advanced technology to engineering services. Mas, F et al., [4] emphasized a continuous evolution of PLM tools and usage to meet the demands of the aircraft's development with very improved performances and also to facilitate the flows of information between all the processes throughout the service life of the airplane. Mas, F et al., [5] proposed to develop an industrial Digital Mock Up (iDMU) to collect the information related to functional design plus all the information related to industrial design: manufacturing and assembly process, associated resources. It reiterates the functional design and industrial design are part of a single design process. Butterfield, J et al., [6] showed the integrated design framework used in the conceptual development of aircraft from a manufacturing perspective. Corallo, A [7] emphasised a PLM strategy to integrate all elements such as people, processes, systems and information that participate in product development. Mathieux, F et al., [8] explored the opportunities and limitations of connecting CAD software and PLM systems with eco-design software tools. Vila, C et al.,[9] proposed an approach to green product lifecycle involving mainstay phases: design, manufacturing and service, including usability and renewal. Author suggested a framework for sustainable product development that takes the whole product lifecycle into account. Moreira, N et al., [10] conceptualized the products development process can be used to improve the production and acceptance of ecological textile systems for the aeronautic completion industry and decrease its ecological footprint from the PLM perspective. Greives defines, the PLM is an integrative information-driven approach comprised of design, processes/practices, and technology to all aspects of a product's life from its design through manufacture, qualification and certification. PLM aims to play a core role in enabling the digital transformation in industry. Product data management (PDM) is interchangeably used in place of PLM where the design data and drawings have been effectively maintained including the release process. In design and manufacturing, several activities rely heavily on CAD data. This includes the use of surface geometry for mesh generation in finite element analysis and the creation of 3D solid models that are pivotal for NC machines and 3D printers in part and tool production respectively. Additionally, 2D contour data is crucial for machinery such as waterjet cutters and composite ply cutters, which cater to tooling and fabrication tasks. Furthermore, 3D contour data is utilized by laser projection systems to support composite layup and part assembly processes. Another significant application is the use of NMG surface data, which facilitates the outer contour inspection of parts using laser scanners. The current PLM system has not encompassed the complete lifecycle data throughout all product development stages, particularly for composite parts. In this paper, we aim to present a framework for incorporating all lifecycle data for design and manufacturing into the PLM system, using examples drawn from typical aircraft wing development. The novelty of this work lies in the fact that every piece of CAD data used throughout the product lifecycle is appended to the corresponding part and assembly models within the PLM system. In the rest of the paper organized as follows. Section II describes product data management, including the current practices of the design and drawing release process. Section III illustrates the data flow throughout various phases of product development. Section IV elaborates on the integration of data and its implementation in the PLM system. Conclusions are provided in the final section.

II. DETAIL DESIGN AND PRODUCT DATA MANAGEMENT

This section aims to provide an overview of the detailed design process, encompassing CAD model and drawing generation, as well as the

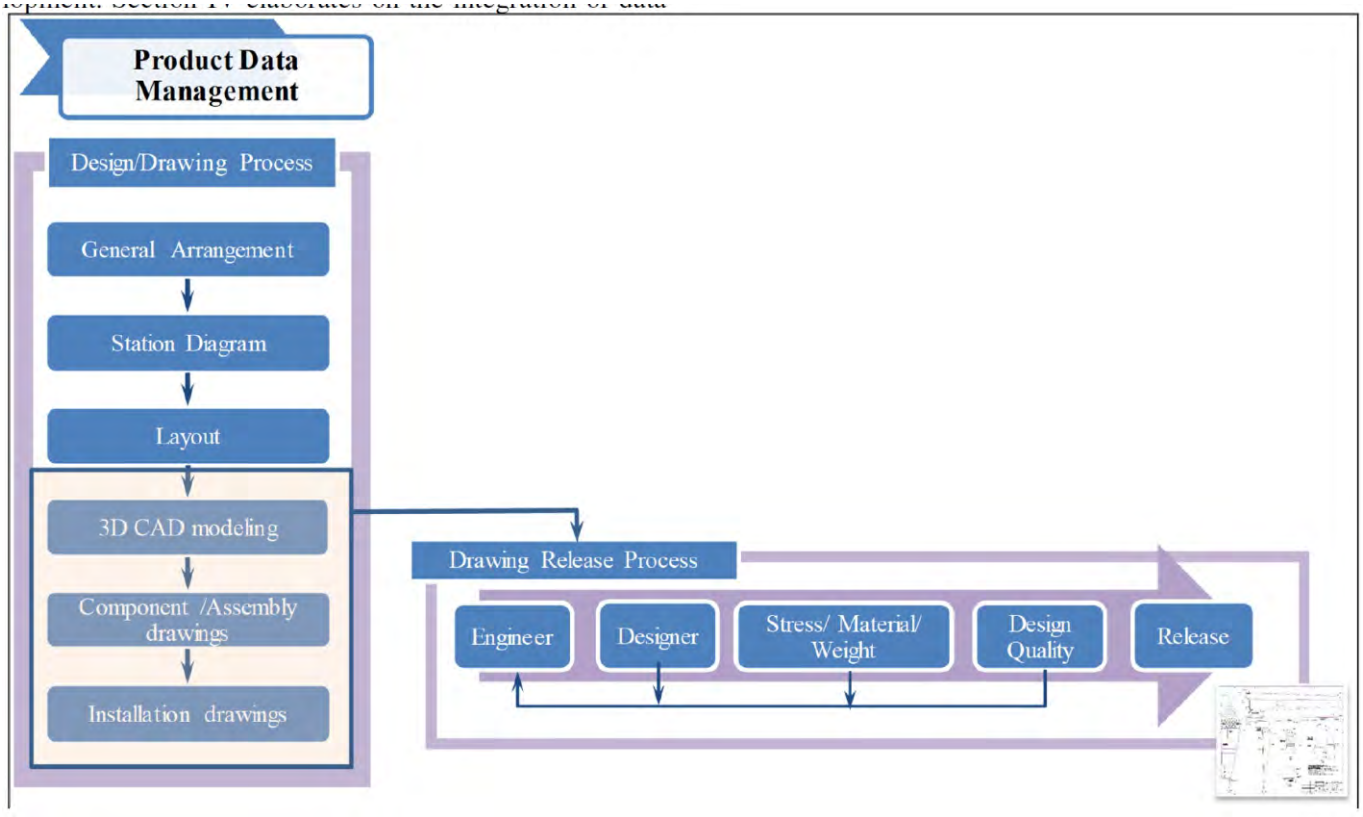

Fig. 1 Typical drawing and release process

product data management (PDM) process, which includes the drawing release procedure.

A. Design and drawing process

Product requirements are devised into a functional
representation. Once the general arrangement (a three-view drawing) of the aircraft is specified, the station diagram is defined. This functional representation is then transformed into geometric details during the layout design phase. The specifications of each component's geometry, along with their interrelationships, are defined to meet the structure's functional and performance requirements. The entire process involves iterative refinement of component geometry specifications
within the layout, both to meet basic requirements and to address conflicts emerging from tooling, manufacturing, assembly, system interface, and more.

In the design process, 3D CAD models and 2D drawings, including installation drawings, are generated. This design data, comprising both models and drawings, must undergo a structured drawing release process, involving various roles as illustrated in Fig. 1. The release process also addresses change management (CM), incorporating updates to the higher-issue CAD model and drawing that originate from enhancements in design and manufacturing.

III. DATAFLOW TO DIFFERENT PRODUCT DEVELOPMENT PHASES

This section provides an overview of the data flow, with different file formats from the CAD system that are utilized in various activities throughout the product development stages, including the FE environment, tool design, manufacturing, assembly, and quality control. The utilization of CAD data at each stage are briefed.

A. Managing data file format in PLM

CAD software utilized for creating design and manufacturing data serves as the input for various machines, equipment, or other environments. Providing the appropriate file format is vital for ensuring compatibility. The file formats are divided

into two categories: standard file formats and software specific formats. A typical output file formats which are usually provided for various systems and machines as shown in Fig. 2.

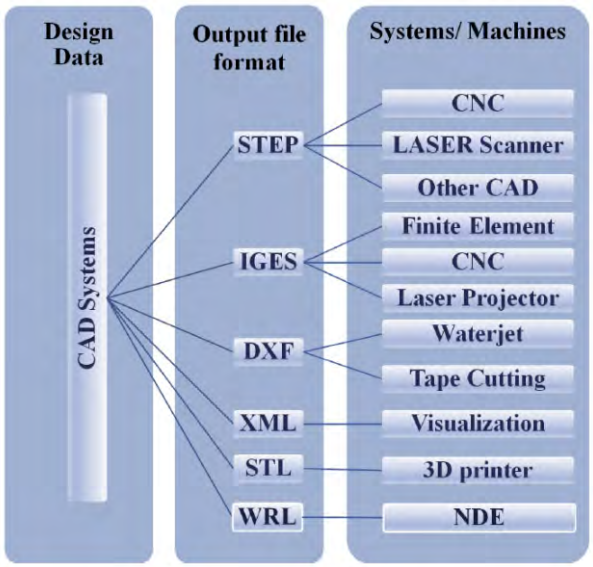

Fig. 2 Different data file format as an input for various systems

B. Data for Computer Aided Engineering environment

A zero-thickness model, using surface geometry in the IGES file format, was imported into the Finite Element environment to generate the 2D mesh. Initially, idealized surface segments for structural elements like skin, spar, rib, etc., were modelled in CAD, considering different zonal thicknesses and material. FE mesh of the wing created in Hypermesh is shown in Fig. 3.

C. Data for Tool Design

Tool design is crucial for the composite part development process, and it primarily relies on CAD data. The CAD data associated activities are briefed in this section. For composite part, a master model, mould and internal tools are essential for processing and curing. Master model (Epoxy block or wood) possessing a complex contour with proper reference was machined using NC machine with CAD data in STEP file format. Composite mould was made from the master model for fabricating the parts. However, sometimes a mould, made of wood or metal, was directly machined using an NC machine. For NC code generation, CAD model data in the STEP format is utilized as input.

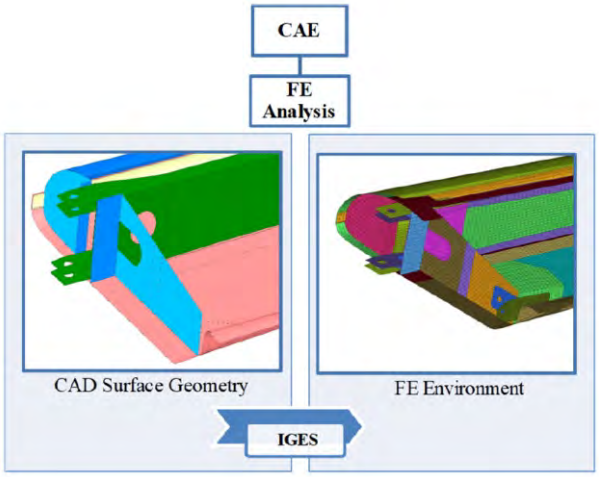

Fig. 3. 3D surface model into FE model of typical wing

Internal layup tools with complex shape were often made using 3D printer (STL file format) or NC machine (STEP file format). The details of dataflow for fabricating various parts are shown in Fig. 4.

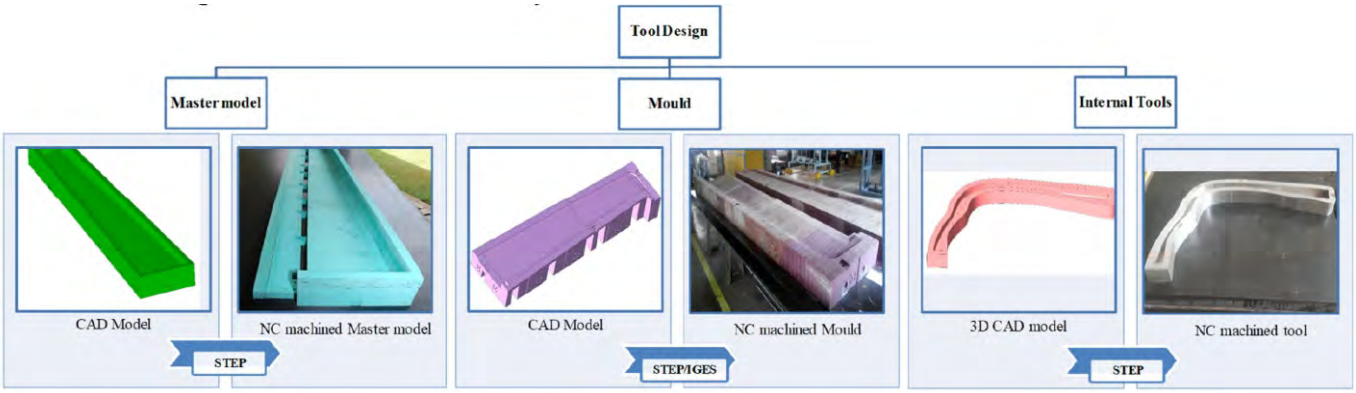

Fig. 4. Dataflow from CAD system for tool design

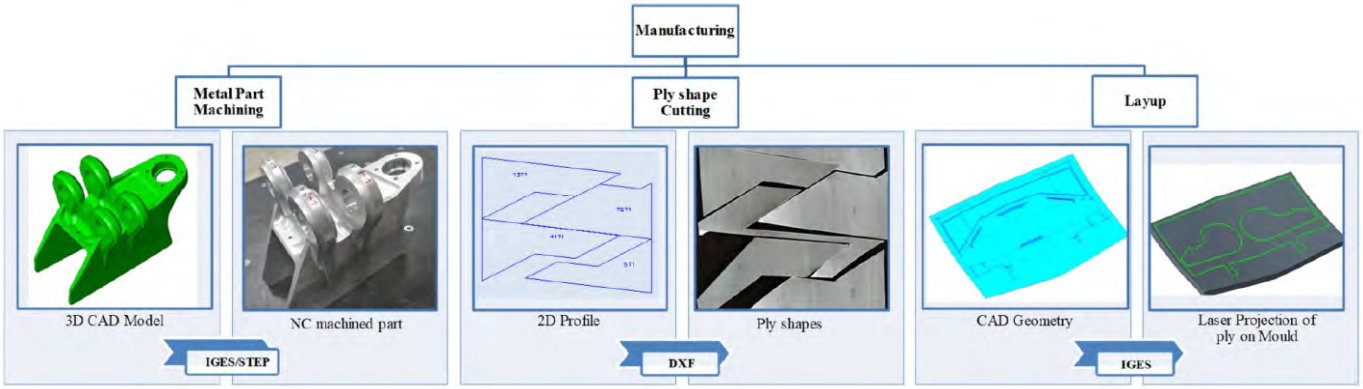

Fig. 5. Data flow from CAD system for manufacturing of a typical metal and composite parts

D. Data for Manufacturing

The manufacturing of a composite part involves several steps once the tools are available. In this sub-section, the details related to manufacturing data inputs for various machines and systems are discussed as shown in Fig. 5. For metal part, data is directly extracted from the CAD model in STEP format which serves as the input for CNC machine. Aircraft composite components feature doubly curved surface. For skin structure, the surface development needs to be performed for getting 2D
ply shapes. These shapes are then cut in the tape cutting machine using a DXF file.

The cut layer shapes at specified boundary locations to stack the plies on the mould to get the required thickness with the guidance of laser projection (LP) system. 3D ply contour data is provided in IGES format for the LP system. This allows each ply boundary on the mould surface to be projected, facilitating the composite ply layup.

E. Data for Assembly

There are many data input support provided for component assembly. Assembly jig settings are usually done with laser tracker. One of the examples to design drill template to transfer the holes to actual structure. A 2D profile data generated from CAD system was used to cut the template in the waterjet cutting machine as shown in Fig. 6.

F. Data for Quality Control

Assembled structure outer contour profile is expected to be within the tolerance with reference

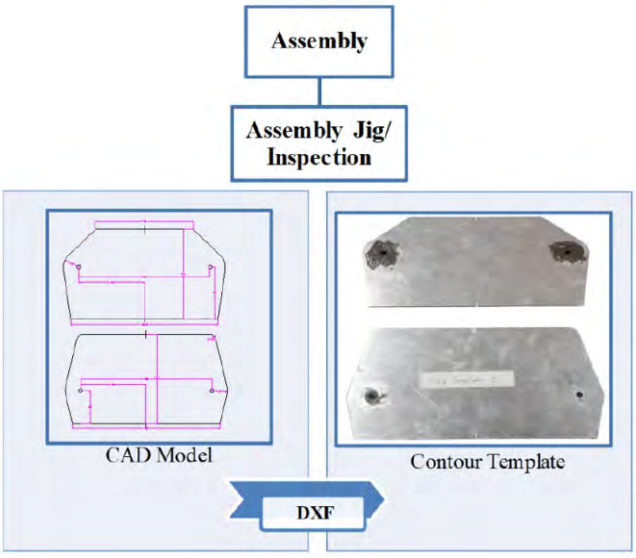

Fig. 6. Data for assembly jig: transfer hole from drill template to structure

to the theoretical outer contour. The laser tracker was utilized to scan outer contour of the assembled structure. The results were compared with the theoretical contour (Numerical Master Geometry-NMG) as an input file in IGES format for the scanner. Part boundary with complex doubly curved part was checked with inspection gauge which was made using 3D printer. Dimension inspection of manufactured part was carried out using this certified gauge.

CAD model in WRL format was provided for C-Scan systems in non-destructive evaluation (NDE) for qualifying the composite part. The details of dataflow from CAD systems to quality control is shown in Fig. 7.

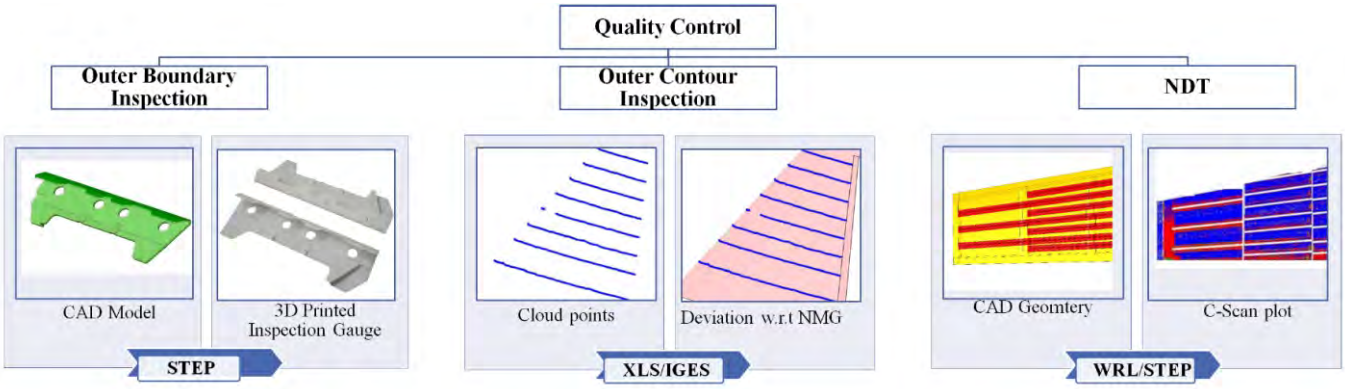

Fig. 7. Data for quality control

IV. INTEGRATION OF DATA ACROSS THE PRODUCT LIFE CYCLE

This section details the integration of data from CAD systems, designed for various downstream activities discussed in the previous section, and its implementation within the PLM system.

A. Integration of data obtained from the CAD systems

In the PLM system, part and assembly models are typically organized in a hierarchy. Corresponding part and assembly drawings, associated with CAD models, also encompass the release process and material schedule generation. In change management, any modification in design and manufacturing is observed and amended, resulting in the subsequent release of higher-issue drawings. This is typically handled in the PDM module. However, other CAD data related to design and manufacturing, particularly those associated with specific parts and assemblies, are usually managed outside the PLM system. For the development of composite parts, the data required for various downstream design and manufacturing activities, as discussed in the previous section, need to be integrated into hierarchical part and assembly

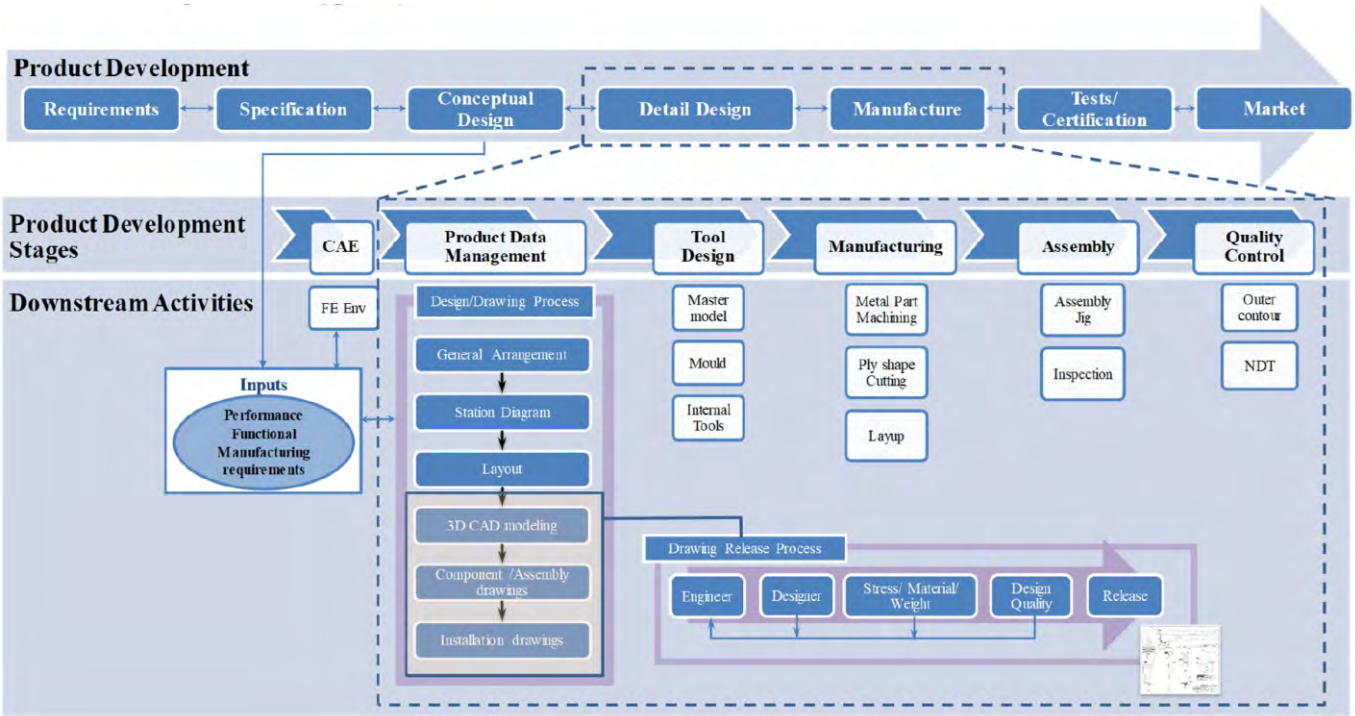

Fig. 8. Integration of design and manufacturing data in the product development of composite parts within the PLM system.

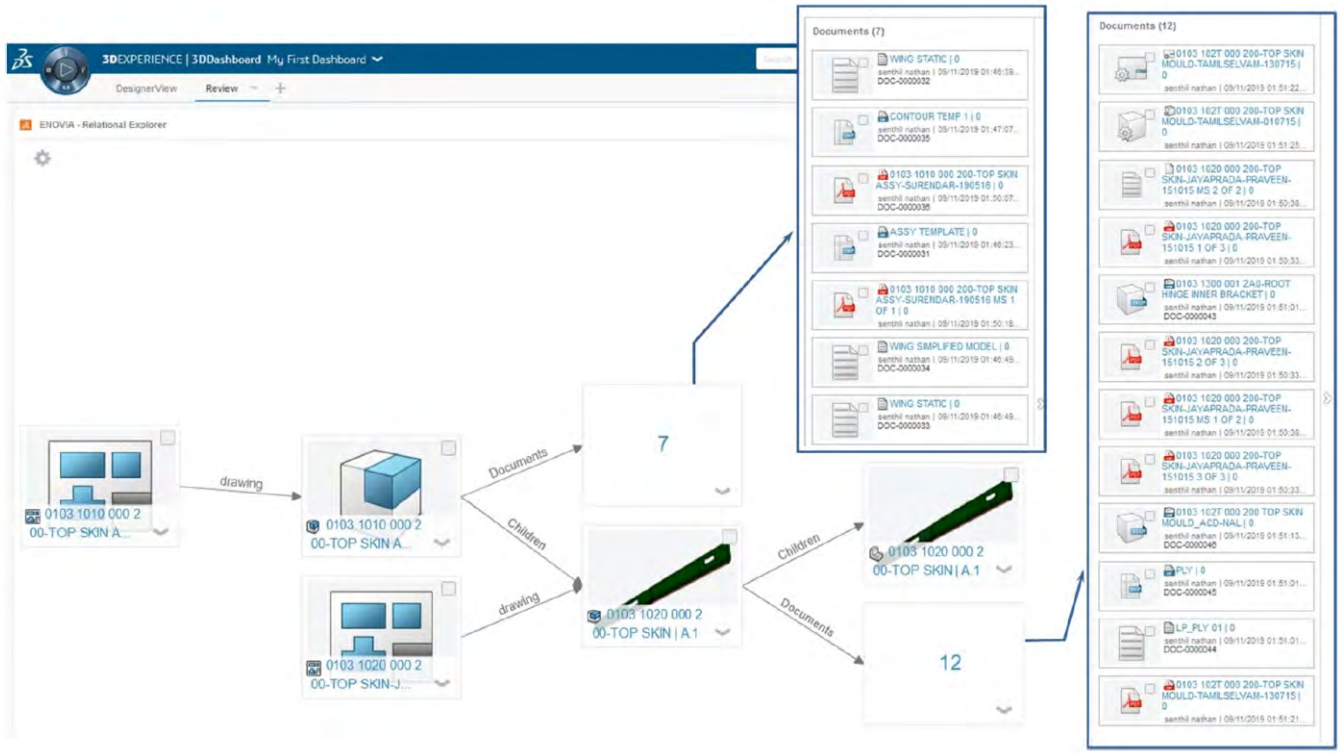

Fig. 9. Data from CAD appended with appropriate part and assembly model of the wing skin in PLM system

models. The integration of CAD data across the design and manufacturing lifecycle, as implemented, is shown in Fig. 8.

Integration of data within PLM at each stage of product development along with the PDM process enhances data reusability and traceability. Furthermore, any changes or updates in the data can be managed with different versions at the appropriate model level, preventing duplication.

The data required for downstream activities were appended with appropriate part and assembly model. 3DEXPERIENCE software was used as a PLM system specifically for the wing of an unmanned aircraft. A typical wing skin and its assembly created in CAD system and corresponding attached data in PLM system is shown in Fig. 9.

B. Implementation of data attached to the parts and assemblies in PLM system

The part level data generated from CAD for various systems and activities are shown in Fig. 10. The CAD model of the component was used to create a 2D drawing. The released drawing, which includes the material schedule (BOM) in PDF format, was appended to the CAD model. The unique feature in this dataflow is that the tool model and drawing have also been attached to the component model. The tool CAD model for NC machining was tagged on to the respective part model.

For composite part manufacturing, data like the ply shape for tape cutting (in DXF format) and ply boundary for laser projection (in IGES format) have been affixed with the skin part model.

The assembly model is the parent structure of the part model. Similar to individual parts, assembly drawings and released PDF drawings were attached to each corresponding sub-assembly level. Data related to assembly, inspection, and FEA information were attached to relevant assembly model, as shown in Fig. 11. The idealized zero thickness (surface geometry) CAD model (in IGES format) was managed for 2D mesh generation in Hypermesh. The input (BDF/DAT) and result files (RES/OP2) were also linked to assembly level. The outer contour data, provided in IGES format for contour inspection using a laser tracker, was

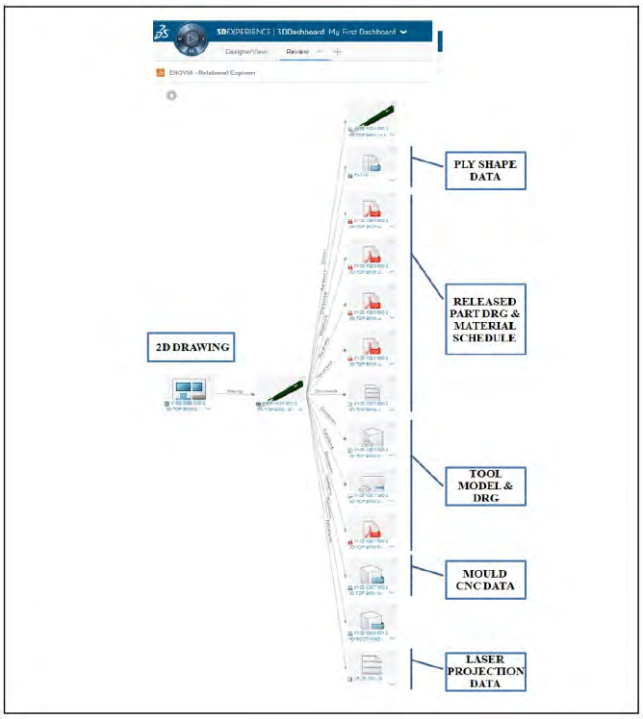

Fig. 10. Typical data from CAD attached with part model

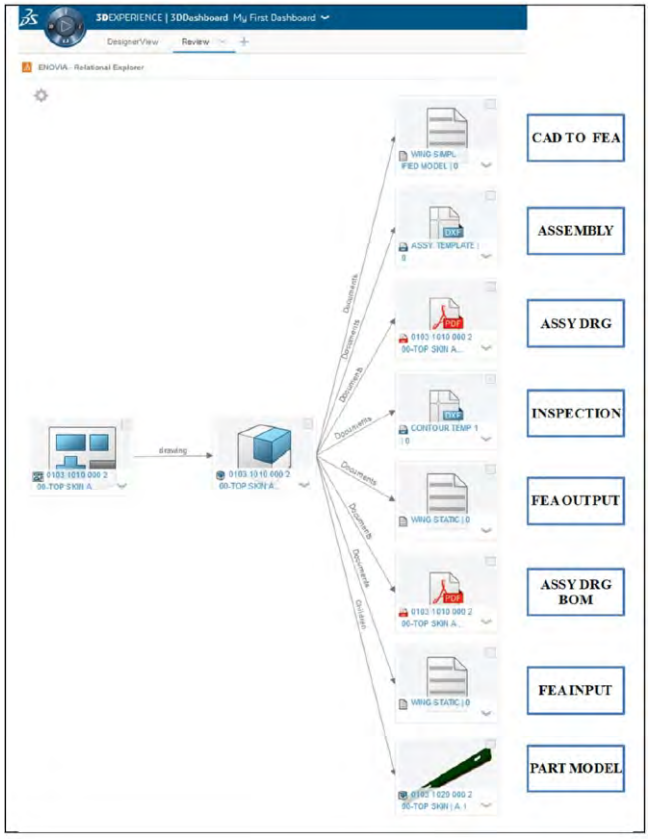

Fig. 11. Typical data from CAD attached with assembly model

managed to meet the quality control requirements.

Complete design and manufacturing data volume from CAD systems for the composite wing is shown in Table 1. From the part level to the final assembly, relevant input data for various downstream activities has been meticulously managed, especially with issue control, to prevent potential duplication.

Table 1. Volume of data provided for various downstream activities for a typical composite part

Part design data, CAD model and drawing (Nos)				
Part drawings	CAD models	Standard parts	-	-
59	54	300	-	-
Tool design data, CAD model and drawing (Nos)				
Tool drawings	CAD models	Standard elements	Jigs	-
52	66	20	03	-
CAD model and data for tooling, manufacturing, assemblyand quality control (Nos)				
CNC	Waterjet	Ply Cutting	Laser Projection	Inspection /CMM
08	125	38	38	18

V. CONCLUSIONS

The integrated data flow pertaining to each stage of product development is presented. The PLM system was effectively utilized to demonstrate the data flow for the aircraft wing. The product structure with multi-level hierarchical part and assembly model was well-defined to append the appropriate lifecycle data in each stage of product development. The proposed methodology enables the full exploitation of the PLM framework along with CAD systems, significantly improving traceability, reuse, and repeatability.

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Implementation of Process Track Sheet (PTS) in Product Life Cycle Management (PLM

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Abstract - Product development within the aerospace and defence research field is a multifaceted and crucial process, necessitating the incorporation of cutting-edge technology while prioritizing safety and reliability. This research paper delves into the challenges encountered during defence product development, particularly when initiating projects from configuration design with limited legacy data, leading to significant obstacles in project execution. The paper highlights the deficiencies in recording and tracking configuration control at the designers' level. To overcome these challenges, the study proposes a customizable documentation process called the Process Track Sheet (PTS), along with flexible guidelines for generating task-specific PTS variations tailored to individual designer requirements. By enabling efficient activity tracking and streamlining evaluation by supervisors, the suggested PTS enhances transparency and cultivates innovation in aerospace and defence product development.

Keywords - PLM, Process Track Sheet, LRU, Checklist

I. INTRODUCTION

In the realm of research and development (R&D) industries, project and product development is driven by many factors such as changing product requirements and the rapid evolution of new technologies. In this dynamic working environment, lack of comprehensive documentation of project activities can lead to cumbersome processes at the designer level. Crucial iterative studies and associated details may remain unrecorded, placing a heavy reliance on the designer's memory. Consequently, challenges arise when a designer departs, leaving a new individual to take over the work. To address these issues, a structured approach is essential to ensure accurate and up-to-date records of project activities, requirements, and remarks.

This paper presents a practical solution to overcome these challenges by introducing the Process Track Sheet (PTS), a well-designed and proven tool that aligns with a checklist-based approach for process completion. The PTS comprises of many attributions of a component the designer intends to work on and the various considerations the designer considers to arrive at a solution which

provides both designers and managers with a comprehensive reference during the design phase and for validation purposes. By adopting the PTS, R&D industries can achieve streamlined project management, facilitate effective communication between designers and stakeholders, and optimize knowledge transfer.

The paper thoroughly describes the design and implementation of the PTS, highlighting its potential to enhance project management efficiency and mitigate risks associated with undocumented data. Supported by real-world case studies, we demonstrate the benefits of employing the PTS in Inboards arrangement of LRUs in LCA AF Mk2 aircraft.

Further this paper presents the customisable guidelines to generate task specific PTS enabling it wide spread adoption in R&D industries, promoting meticulous documentation practices, improving project continuity, and fostering innovation.

II. STANDARDISING DATA MANAGEMENT USING PTS

While the challenges faced in most product development industries are similar, the nature of data they handle varies depending on their specific domains. This necessitates the use of a customizable, standardized tool. Organizations can design and develop such a standardization tool according to their unique needs, but introducing some common elements during the conceptual stage can facilitate systematic and progressive improvements to the tool. This standardized tool is expected to enhance process efficiency and data management.

This paper outlines the design of a Process Track Sheet (PTS) aimed at monitoring activities related to the Inboard Layout of Mk2. The finalization of the Inboard layout is a complex process, requiring multiple iterations based on various design factors, which can create a somewhat uncertain working environment.

The PTS tool is being developed to comprehensively capture all pertinent details of every designer's activities. In this context, the primary objective behind creating the PTS is to establish a well-organized database for recording and documenting these activities. Following are the major advantages of implementing a standard tool like PTS:

A. Monitoring Development Activities

In the area of research and development (R&D) industries, the constant evolution of project and product development is a common occurrence. As a result, the existing design or system may no longer align with the updated product or project requirements, necessitating a redesign or new approach to finding solutions. To effectively manage these changes, meticulous tracking of development activities becomes essential, playing a paramount role in ensuring project success.

B. Smooth Transfer of Duties and Responsibilities

At institutes like ADA, personnel at the working level, particularly PEs, PAs, and CEs, often work on a temporary tenure basis. Consequently, when new individuals are appointed, they might not be fully aware of all constraints that need to be considered. This lack of awareness can lead to considerable time consumption when implementing configuration changes, as the new personnel may not be familiar with previous studies and constraints. This results in increased iterations or repetitions of the same activity, impacting the overall project cycle time and cost.

For instance, when dealing with LRU (Line Replaceable Unit) installation in Inboards Layouts, designers interact with various teams, such as the Airframe team, QA&SEG (Quality Assurance and Safety Evaluation Group), respective systems team, Installation team, and Aero team, to resolve installation-related issues and freeze the configuration. As the project progresses certain issues may emerge, requiring to rework or relocate the LRU in the region.

Without proper records or tracking of previously conducted studies, designers may struggle to recall all the constraints they had previously considered. Moreover, if the personnel working on

the activity change during the process, valuable information about constraints and previous studies may be lost. As a consequence, the number of iterations increases, leading to extended cycle times and higher project costs. Implementing effective documentation and standardising the knowledge transfer practices is crucial for enhancing project efficiency and minimizing disruptions caused by personnel changes.

III. METHODOLOGY

In this paper, we propose an additional layer of documentation called Process Track Sheet (PTS). It's primary goal is to contain comprehensive and relevant information pertaining to each activity. Whenever a designer encounters a new activity, a unique ref ID will be generated to represent the activity and this enables designer to feed the relevant data to the generated PTS. To enhance efficiency and effectiveness, we propose leveraging digitalization techniques through software programming, creating a PTS software database capable of capturing essential inputs for activity identification. The sheet will be organized into different sections for ease of handling, tailored to suit the nature of the information.

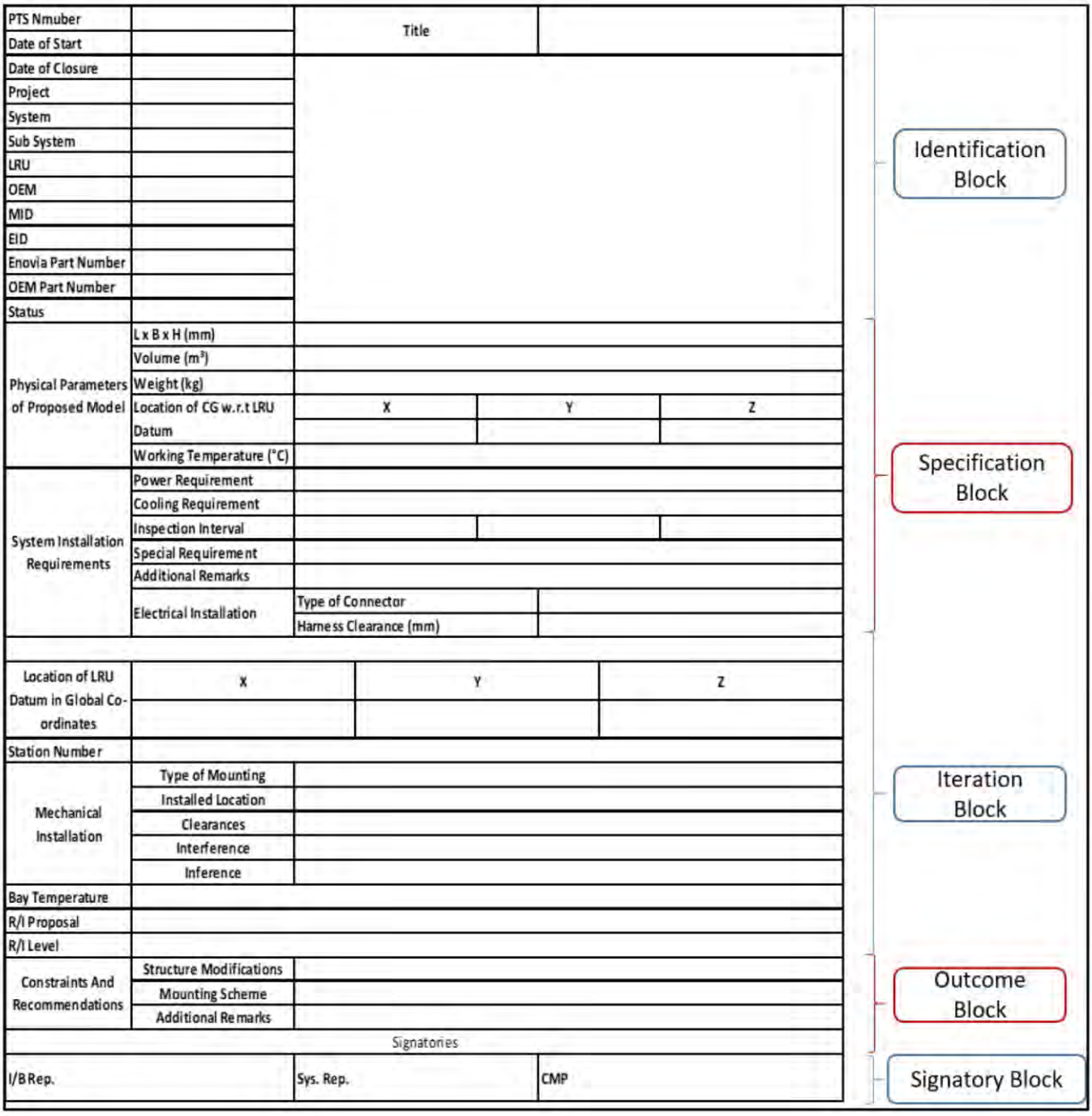
The information collected through the PTS will be saved in the system, accessible to authorized personnel whenever required. By using the PTS ID number, previously saved activities can be retrieved, allowing updates to the data as needed. Furthermore, archived data will be stored as backup for future reference, ensuring data integrity and traceability.

We envision implementing this methodology in applications where the working environment is highly ambiguous, such as the Inboards Design Layout in aircraft design. The Process Track Sheet for Inboards Layout will include LRU specifications, installation requirements/constraints, and any other information necessary for finalizing the Inboards Layout Design. Additionally, provisions will be made for recording iteration details and respective inferences made during the design process. This innovative approach aims to streamline project management and knowledge transfer, particularly in complex and evolving research environments like aerospace and defence industries.

IV. OUTCOMES OF PTS

This paper proposes the implementation of a PTS to use in the development of inboards layout of LCA AF Mk2. The PTS outline is structured with distinct blocks for common details, as illustrated in the figure 1. This approach simplifies the design and enhances overall comprehension. These blocks collectively establish a unique identity for each Line Replaceable Unit (LRU), complete with a distinctive ID for precise LRU identification. This ID enables authorized personnel to access PTS details at a later time, affording them the capability to make edits or updates as needed.

The identification block holds details regarding the identification of the PTS including LRU, Project details, Date of opening and closure and the references to other related documents to the LRU such as installation diagrams. Each organization can adopt a unique way of assigning ID to the PTS based on the details entered. Specification block is intended to record the physical parameters such as LRU dimensions, working temperature, installation requirements and cooling requirements. Additional remarks can be added based on necessity. The inclusion of an iteration block into PTS helps to include information regarding the installation study carried out for the LRU. It includes location, physical clearances, zone temperature, R/I (Removal/Installation) level, etc. with respect to a specific iteration for a given LRU. The constraints and recommendation section in this block captures the details of other affected parts/ components, due to that specific iteration or the decisions undertaken from meetings. This can help in track of affected parts and decisions made. The outcome block is incorporated for the designers to fill the outcome of the iterations carried out. The designer can utilize the additional remarks column to highlight data such as system/LRU (if any) affected due to that specific iteration, decisions made, etc. Provision for validation and authorization by stakeholders are provided in the Signatory block added at the end of PTS.



PTS Nmuber		Title			
Date of Start					
Date of Closure					
Project					
System					
Sub System					
LRU					
OEM					
MID					
EID					
Enovia Part Number					
OEM Part Number					
Status					
Physical Parameters of Proposed Model	L x B x H (mm)				
	Volume (m^3)				
	Weight (kg)				
	Location of CG w.r.t LRU	X	Y	Z	
	Datum				
	Working Temperature (°C)				
System Installation Requirements	Power Requirement				
	Cooling Requirement				
	Inspection Interval				
	Special Requirement				
	Additional Remarks				
	Electrical Installation	Type of Connector			
		Harness Clearance (mm)			
Location of LRU Datum in Global Co-ordinates	X	Y	Z		
Station Number					
Mechanical Installation	Type of Mounting				
	Installed Location				
	Clearances				
	Interference				
	Inference				
Bay Temperature					
R/I Proposal					
R/I Level					
Constraints And Recommendations	Structure Modifications				
	Mounting Scheme				
	Additional Remarks				
Signatories					
I/B Rep.		Sys. Rep.		CMP	

Figure 1 Outline of Process Track Sheet for Inboards Layout of LCA AF Mk2

Furthermore, the incorporation of remark columns within the relevant blocks is deemed essential. These columns serve as a repository for recording important comments pertaining to the design and development of each LRU. This documentation proves invaluable, especially for novice designers, as it provides insights into the rationale behind any modifications or design prerequisites. Ultimately, the PTS for each LRU can undergo authentication by the corresponding authorized personnel or team.

As depicted in Figure 1, this design approach simplifies the overall structure and enhances comprehensibility. These individual blocks collectively form a distinct identity for each Line Replaceable Unit (LRU), marked with a unique ID for precise LRU identification. This ID enables

authorized personnel to access PTS details at a later stage, facilitating edits or updates as needed. Inclusion of remark columns within the relevant blocks is essential to document noteworthy comments pertaining to LRU design and development. These remarks serve as valuable insights for new designers, offering clarity on the rationale behind any modifications or design prerequisites. Ultimately, the PTS for each LRU can undergo

V. SMARTER PTS THROUGH DIGITAL ENHANCEMENTS

To enhance the user-friendliness of the PTS (Process Track Sheet), we can leverage digital techniques effectively. By introducing a user-friendly interface, we enable the seamless input of data into a centralized PTS database while also facilitating easy retrieval of specific information when needed. This interface, driven by program coding, not only enhances efficiency but also adds a layer of intelligence to the PTS system. Figure 1 shows one such user interface created for PTS which can be run as a program with the help of VBA (Visual Basic for Applications) Excel coding.

The interface is customizable based on the requirements, ease of operation and the type of data to be included. Different blocks of PTS are categorized into different pages such as User Interface, Identification, Iteration, Specifications and Outcome pages as shown in Figure 2. This makes it simpler in interaction and easier to handle. The sheet is programmed insuch a way that the entered details can be saved efficiently as a softcopy.

While entering data related to a new activity, based on the input given on the identification block, a unique ID will be generated automatically by the PTS. A separate array will be created with this ID as it's address and data which are being fed to the PTS software will be save into this array upon saving the data. In case of updating or modifying an existing LRU details the old details will be back up as a database which can be accessed whenever required. Hence, PTS implements the feature of tracking the full history of an activity.
One of the primary benefits of this digital transformation is the efficient storage of data within software, resulting in improved accessibility and availability. Authorized user can now access the PTS from virtually anywhere, ensuring that crucial information is at their fingertips when required. Additionally, the digitization of the PTS fosters data reusability, a significant advantage. This means that data can be repurposed, reducing redundancy and promoting a more sustainable and streamlined workflow within the organization. In essence, embracing digitization techniques not only modernizes the PTS but also optimizes its functionality for greater efficiency and productivity.

The PTS can be made more user friendly by releasing as an application that can be installed and used by the respective personnel upon authentication.

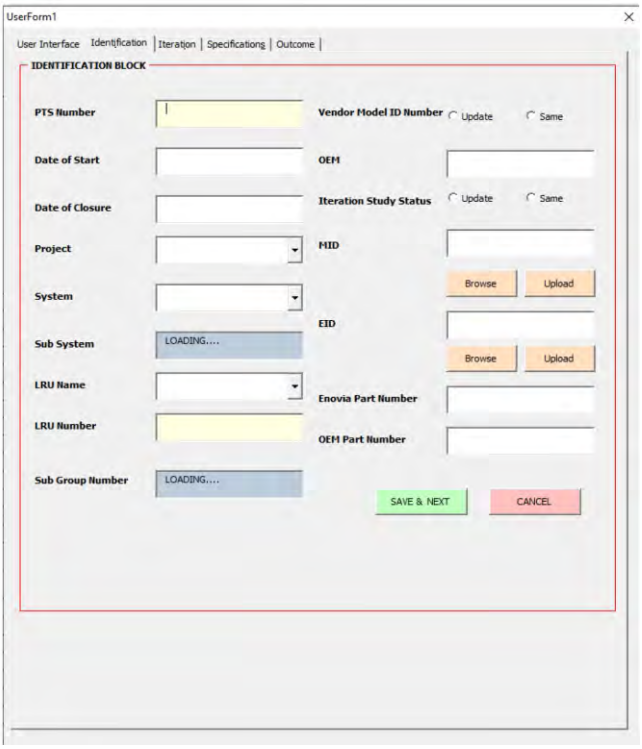


Figure 2 User interface model for PTS

VI. RESULTS AND DISCUSSIONS

In the present era, the Research and Development industry is highly uncertain and challenging.

The implementation of a well-organized Process Track Sheet (PTS) in an organization yields the following outcomes:

A. Standardized Procedure

The PTS enables the adoption of a standardized procedure for design and development activities within the organization.

B. Meticulous Documentation

All requirements and constraints related to each activity are meticulously recorded in the PTS. Designers can easily refer to this information as needed, reducing reliance solely on their memory. This minimizes the risk of neglecting crucial requirements during multiple iterations.

C. Consistency in Process Flow

The PTS facilitates consistent process flow within the organization by reducing redundancy caused by uncertainty. It ensures that the status of every activity is continually reviewed and recorded, promoting a smooth transfer of knowledge.

D. Legacy Data And Optimization

Serving as a repository of activities performed with associated constraints and requirements, the PTS aids designers in arriving at optimal solutions with fewer iterations. Clear definitions of iterations and their results eliminate the chances of repeating the same processes, resulting in considerable savings in working time.

VII. CONCLUSION

Implementing the PTS brings several benefits, including standardized procedures, reduced risk of neglecting crucial requirements during iterations, and improved process flow consistency. The PTS serves as a legacy database, assisting designers in arriving at optimal solutions with fewer iterations, leading to considerable savings in working time.

The Process Track Sheet offers an effective solution to overcome challenges in aerospace and defence product development. It's customizable nature and flexible guidelines facilitate wide-spread adoption in R&D industries, promoting meticulous documentation practices, improving project continuity, and fostering innovation. By using PTS, organizations can achieve streamlined project management, enhanced productivity, and successful adaptation to the ever-changing work environment. Future research and application of the PTS in broader sectors shall have a major impact on the project life cycle management.

ACKNOWLEDGMENT

We would like to thank ADA for providing necessary infrastructure and thoughtful insight for carrying out. We would also like to thank colleagues for supporting the implementation of Process Track Sheet and providing their valuable feedback

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Product Life Cycle Process & Management for Human Spaceflight Missions

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Abstract - Human space missions differs from typical spacecraft due to the inherent risks posed due to the presence of the human life. It involves the re-assessment of current systems with respect to human safety, introduction of innovative methods in order to mitigate the risks. Product lifecycle management (PLM) is an effective, integrated and information driven approach which allows us to execute complex spacecraft missions with reduced risk and higher probability of mission success. PLM for human spaceflight mission integrates human rating approaches such as hazard analysis and risk management to achieve the highest level of reliability and safety.

This paper discusses about the new approaches and the methods to implement them using PLM at the system level.

Keywords - Crew Capsule, Human Spaceflight, Hazard, Risk, Safety

I. INTRODUCTION

A product (in this case, a human rated spacecraft and rocket) is the combination of subsystems that function together to meet the mission goal. The subsystems include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for achieving the mission.

Spacecraft technology demands highest level of technical prowess, quality & reliability, safety aspects and those too within stringent budget and schedule constraints. Any failure can not only lead to huge monetary loss but also that of strategic applications. With the beginning of new human space flight era where agencies are planning for long duration space habitation, tourism and deep space mission, integration of the human safety requirement in the mission design has become essential.

PLM for Human spaceflight mission brings in a paradigm shift in the field of satellite missions by using robust, reliable end to end digital tools for validating the design by virtual modelling the system and thus significantly reducing the design iterations as well as effectively carrying out troubleshooting.

II. HUMAN SPACEFLIGHT LIFECYCLE PROCESS & MANAGEMENT

Figure-1 shows the key PLM processes which the Crew Capsule undergoes during its lifecycle.

The overall mission lifecycle has been divided in to four major verticals-

1. System Design
2. Technical Management
3. Realization
4. Mission Execution, Recovery & post-flight analysis

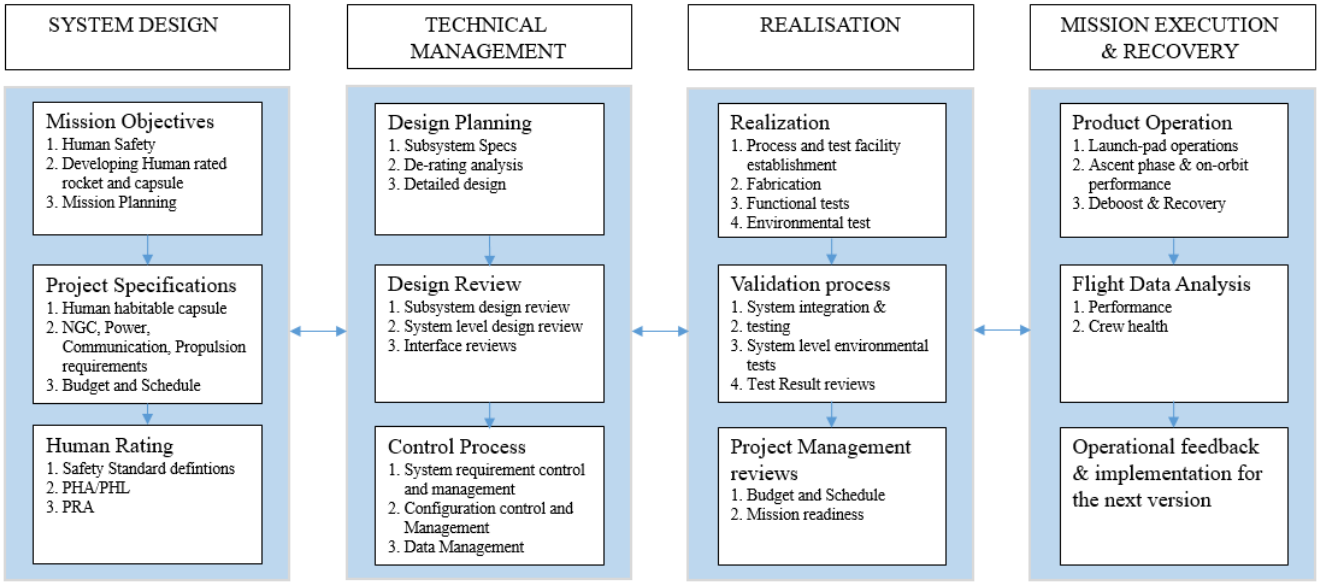

Figure 1 Lifecycle of Human Spaceflight Missions

A. System Design

Spacecraft system design consists of three parameters.

1. **Mission objectives:** Typical spacecraft system design starts with defining mission objectives. For example,
   i. Mission objective of a typical remote sensing spacecraft is imaging in various spectral bands, spatial resolution and swath.
   ii. Mission objective of a Geo stationary spacecraft is to provide communication, navigation services etc.

   For human spaceflight mission, mission objective is to transport humans using a safe habitable capsule via human rated rocket and bring them back safely at the predefined touch-down point after on-orbit operation. Human safety is at the core of such missions and rocket, crew capsule and even the mission planning is carried out by keeping this factor in mind.

2. **Project Specifications:** For a typical spacecraft, from the mission requirements, project specifications are derived. Such as defining the payload configuration, orbit selection & attitude control, mass, power, propulsion & communication requirements. However, in a human mission, apart from defining above mentioned specifications, human centric systems are also defined. These include cabin pressure control, thermal and humidity control, monitoring and removal of trace gases, personal hygiene, food, water & oxygen supply, health monitoring and emergency medical services, fire detection and suppression system. These specifications are split into rocket, crew capsule & ground support system requirements.

   One of the exclusive system of human mission is the crew intervention system which integrates the crew with various onboard system equipping the crew to take decision and control in case of any onboard failures.

   While defining project specifications, budget requirement is generated and schedule is also prepared to define and track project milestones.

3. **Human Rating:** The Human safety definitions are converted into standards & product based requirements. It defines following to be incorporated to meet the human rating requirements
   1. **Usage of heritage systems with demonstrated reliability** - The best measure

of reliability is having enough flight heritage. The subsystems selected for human spaceflight (Spacecraft and rocket) should have demonstrated reliability in the form of flight heritage. Crucial technologies which have already demonstrated its robustness in generic missions are preferred over new designs. The integrated spacecraft and rocket are also made to undergo at least two successive successful mission before the actual human mission. In this way the heritage of end to end mission including integrated spacecraft, rocket, ground systems and recovery aids is demonstrated.

2. **Re-evaluating and enhancing design margins** – For a human rated mission, all design margins are revisited and increased suitable to human mission by either redesign-ing or by derating the systems. For example, the load bearing structure member have to demonstrate 1.4 factor of safety instead of 1.25 (for typical aerospace application). A systematic approach is followed to establish these margin in each systems and a thorough review process to ensure the implementation. The batteries used inside crew cabin are also kept at lower state of charge as compared to its allowed limit.
3. **Mission design** – The human rated mission is re-designed with ascent trajectory to contain the re-entry load experienced by the crew within human survivable limit during abort. The Orbit selection is carried out to have
   - 3.1. Landmass avoidance during abort and nominal re-entry scenerio
   - 3.2. Minimum radiation effects on capsule.
   - 3.3. Maximum de-boost and recovery opportunities
   - 3.4. Daytime recovery of capsule in nominal and abort scenerio
   - 3.5. Major operation should have ground stations visibility
   - 3.6. Minimum space debris collision probability
4. **Ergonomic Design** – The crew has to live within the confined space for 3-5 days. Thus the crew capsule is designed with minimal obstructed items and maximizing the free space for crew. The necessary display and control switches are made easily accessible to crew. The crew suit and seat are also designed specific to crew anthropometry which aids comfort and safety.
5. **Material & processes selection** – The material prone to fire, stress induced cracking and outgassing are strictly prohibited in human spaceflight missions. Even in case of fire, the material selected should not produce toxic gases in capsule. The material prone to arc tracking are also avoided and extra insulated wires are used for better safety. Traceability from raw material to component and stock is established to ensure proper up-screening methodology.
6. **Qualification plan** – The human rated mission has additional phases such as abort and re-entry, which calls for qualification to such higher level of environmental loads (shock, thermal and vibration).
7. **Hazard analysis, risk assessment and mitigation** – Hazard is defined as any failure leading to loss of crew. Various subsystem failure conditions are defined as per their severity which compromises the crew safety. Each failure condition is analyzed for its probable risk and appropriate mitigation techniques are incorporated in system design or operation to ensure crew safety. For example, any failure in atmospheric phase of mission require a quick response for which provision of escape system for crew is made available. Another example of mitigation is that the energy sources are also protected with the safety fuses inbuilt to avoid any fire in case of short circuits.
8. **Software safety standards** - Software being an important part of the avionics system in the spaceflight, Software Safety Standards are defined to that addresses the complete software life cycle activities to be followed for safety critical software systems depending on the criticality level. Hazard analysis are also carried out for software to function safely. Independent validation and

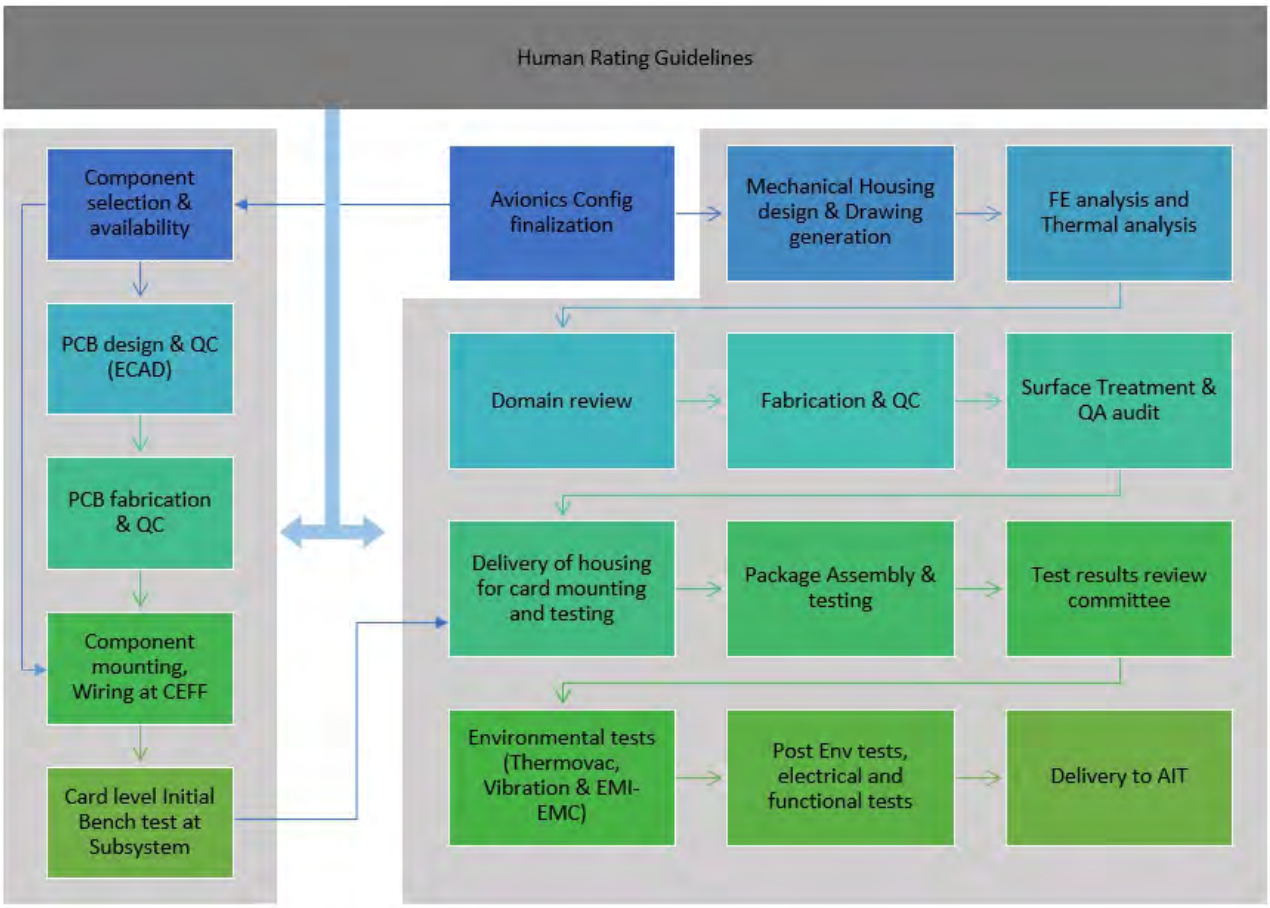

Figure 2 Lifecycle of Avionics package

verification is an important aspect of safety standards.

9. **Crew Training** – The integration of crew to onboard hardware is critical to the success of mission. Adequate crew training in terms of technical details about designs and operations are provided to increase their situational awareness enabling them to act optimally in emergency situations. Various crew training simulators are developed for their hands-on experience training.

B. Technical Management

The technical management processes are used to generate the technical plans, to manage communication across interfaces, to assess the progress, and to aid in the decision-making process.

It consists of three phases: design planning, reviews and control processes to ensure the system and subsystems requirements are coherent.

1. **Design Planning** - A preliminary configuration of crew capsule and rocket is arrived at using various system engineering tools such as feasibility study, accommodation study with mass-power & propulsion constraints. The list of subsystems and their specifications are derived from the system level requirement. For example, the solar panels and relevant mechanisms are configured considering the overall power requirement, attitude of spacecraft. The battery is designed to support the capsule during the eclipse, any emergency abort and post-touch down support till the recovery. The oxygen tanks are sized to meet the cabin pressure requirement and to top-up the oxygen being consumed by the crew.

The de-rating analysis is also an integral part of design planning by the SDAs (System Development Agency). For example, the solid rocket boosters MEOP (maximum expected operating pressure) is derated to increase the structural margin. Each electronic component is analyzed for its nominal voltage and current which are ensured by design to encompass within its derated values of absolute maximum rating.

Various SDAs are identified to carry out the detailed design of subsystems.

2. **Design Review** - The PDR (preliminary design review) validates that the design carried out by SDAs meets all system requirements with within the cost and schedule constraints. To ensure all functional requirements are met in the design; each subsystem undergoes thorough reviews by various domain experts. Interfaces with other subsystems are also defined and reviewed. The Critical Design Review is carried out as a precursor to the starting of the fabrication.
3. **Control Process** – The control and communication of any system requirement change is a major challenge. The lifecycle of such missions are quite long where even system requirements and technology can also change. To confirm the changes envisaged are not deviating from the system requirements, Various committees such as System requirement control & Configuration control management are established to ensure any such changes in the system requirement are translated to subsystem functional requirement. Such changes are documented, reviewed and communicated to relevant agencies.

C. Realisation Phase

This phase includes hardware realization & validation processes after the completion of necessary design reviews.

1. **Realization:** An example of an avionics package is taken here to explain the product lifecycle of an avionics package using indigenous PLM software. Figure 2 shows the processes involved in realization starting from avionics configuration finalization till delivery to spacecraft level integration. The SDAs upload the component list & footprint dimensions to PLM tool which acts as an input to the component selection as well as mechanical housing design. Exhaustive database of components is available as a part of PLM software. Upon the selection of components, the component placement is carried out by CAD team. The human rating guidelines are also incorporated in the PCB design, component selection, wiring, material selection, process selection & margin of safety in the PLM tool which keeps a check and brings out any deviations from the guidelines.

The PCB fabrication is carried out along with quality check to meet the stringent requirements. Parallelly, after the initial screening, the components are delivered to wiring agency just in time of PCB delivery. The PCB wiring is taken up with SMT components first followed by through-hole component wiring. The wiring stage follows visual inspection by QC and clearance for functional testing.

The PCB dimensions' and mass act as inputs to mechanical housing design team to initiate the design. the team carries out thermal and FE analysis to meet the thermal, stiffness and strength requirement of the package as defined by Environmental test specifications. The design undergoes reviews and then for fabrication, surface treatment and delivery to mount PCB. After the full package assembly and testing, results are presented to test results review committee which allows the package to undergo environmental tests. Post-environmental electrical and functional check, the package is delivered to Spacecraft integration.

The PLM tool incorporates all the lifecycle

data (fabrication, deviation, corrective actions and functional test data) of component, PCB & mechanical housing.

2. **Validation process**- Once every package undergoes realization cycle as shown in figure 2, it enters validation process at integrated testing phase. Even though each package undergoes a detailed test at subsystem level, the integrated testing phase confirms the interface design in flight configuration. The PLM tool integrates the Test data from subsystem level & integrated testing phase which can be used for system level integration and testing. This phase wise record of subsystem test data helps brings out any deviation or anomaly at the earliest which helps in timely correction. The integrated tests on the spacecraft are carried out using this PLM tool. Upon the completion of the integration phase, the spacecraft undergoes the environmental tests to establish the margin and flight worthiness of the integrated spacecraft. Non-conformance management is established to assess any deviations from the specifications and provide corrective actions or waivers. The test results generated in each phase undergoes rigorous test results review in order to assess the flight worthiness of all systems.
3. **Project Reviews:** Periodic project management reviews are also a critical part of realization as it deals with mission readiness schedule and budget constraints.

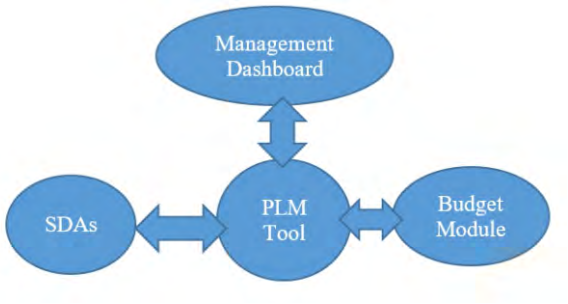

Figure 3 Budget module in PLM tool

1. **Budget management, Scheduling & mission readiness:** The traditional budgeting methods takes months to prepare and weeks to update and requires rigorous follow up. The budgeting criteria and line items are driven by finance and do not maintain the operational details that really drives the project. The budget module in the PLM tool is a single solution that is deployed across the projects, finance and operations to reduce the time and effort required to build and reforecast budget.

Budget module is seamlessly integrated with the PLM tool as shown in Figure-3. The budgeting process for budgeting begins in budget with the identification of a project for which budget will be built. The budget module will save time and

Create Project Budget	Build Project Budget	Analyse Budget	Iterate changes to budget	Summary views
• Existing Project budget template available • Create New budget	• Spacecraft cost (production, testing and management) • Crew training • Launch cost • Operational and recovery cost	• Resource analysis and re-allocation • Identification of long lead items • Resource scarcity among different project	• Preparation of Draft budget document • Comparison of financial sanctions with draft budget • Create new version of budget	• Subsystem status Dashboard • Project allocation dashboard • Expenditure dashboard

Figure 4 Budget process flow

effort by being able to quickly find existing project budget or create new budget. The budget module also includes the status field that can be used to monitor the progress of assigned budget and quickly identify budget that are incomplete. The total project cost is estimated using the spacecraft cost (production, testing and management), crew training, launch cost, operational and recovery cost. The budget management is a major indicator of the project progress and is integrated to the PLM tool to track the spending and balance.

At any time, budget module can quickly assess gaps between demand and capacity. The budget team can go through multiple iterations of the budget before finalising the final budget requirement. Summary views consist of subsystem status, project allocation and expenditure dashboards. This helps in time saving and execute the project with confidence that is consistent with the strategic and financial plans of the organisation.

Standard scheduling tools such as Work breakdown structure and Gantt chart are integrated in the PLM tool which enables the project to optimally plan the activities and deploy the resources accordingly. The PLM tool prompts the concerned agency about the next activity scheduled to plan their activity accordingly.

It also provides the information of each subsystem and overall spacecraft so that management can intervene to data.

After recovery, post flight data analysis is carried out which gives the in-flight performance of all subsystems and crew health.

Due to the systematic approach taken during the lifetime of capsule, in the end of the flight data analysis, feedback is available to mission planning as well as SDAs which can refine the requirement for future crew capsule.

III. CONCLUSION

The project management of any satellite system is complex and challenging in itself. The human spaceflights mission pushes these challenges even further to ensure the human safety during the entire lifecycle. This paper discusses the new approaches being introduced in human spaceflight and usage of PLM tool to successfully implement these approaches to mitigate the risk and ensuring the mission success within budget and schedule constraints.

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Driving Engineering and Manufacturing Efficiencies Through Digital Thread

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Abstract - In a fast-moving competitive world, innovation occurs at the intersection of multiple domains and manufacturers strive to deliver products with personalized features, on schedule, on price leveraging diverse supply chains. However, traditional engineering ecosystems contain a plethora of legacy systems leading to silos of information that lead to costly errors, lack of traceability, manual workarounds, hampering competitiveness and profit margins. A typical enterprise needs to deal with these challenges across the discrete manufacturing space. The digital thread construct spans across sales configurators, pricing engines, CAD, PLM, and ERP systems, and ultimately delivers digital work instructions to the shopfloor via MES. This seamless thread ensures collaboration, an effective use of configuration lifecycle management processes, and breaks silos of information across multiple enterprise systems. This paper presents how an enterprise could measurably improve their business metrics like "Time taken from Order to Delivery" by implementing a digital thread across the ecosystem.

Keywords - Digital Thread, Discrete Manufacturing, ERP, NPI, PLM

I. INTRODUCTION

Over the last few years, one can observe a trend in engineering enterprises to extend the breadth of their product offerings with a renewed push to create personalized smart products as a differentiator. Consequently, there is a need to have clear data ownership and a single source of truth of the product data through its maturity journey from ideation to shopfloor and thereafter. However, the silos of information across multiple enterprise systems and unharmonized data models lead to disconnected system of information and this leads to a costly manual workaround, data re-entry and errors. A digital thread construct can span across sales configurators, pricing engines, CAD, PLM, and ERP systems delivering digital work instructions to the shopfloor via MES. The thread also has potential to span beyond the manufacturing shopfloor into field servicing of devices. This seamless thread ensures collaboration, without loss of context and breaks silos of information across multiple enterprise systems. This paper attempts to highlight the benefits, practical examples and approach to implementing a digital thread across enterprise.

II. THE PROBLEM STATEMENT

While businesses strive to be innovative, agile and first to market with their product, they are hampered by inefficiencies in their existing IT ecosystems. Some of the challenges are listed in Figure 1. Legacy IT systems have traditionally been tuned to be Systems of Record and have evolved to deliver

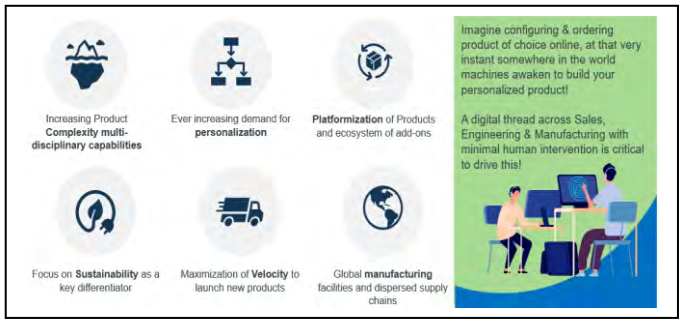

Figure 1 Hurdles in digital thread initiatives

legacy products. The IT ecosystem struggles to deliver the newer generation of products as products are multi-disciplinary and are often designed as "Platforms" to add services and features as desired by the customers.

III. SOLUTION OUTLINE

Product Lifecycle Management (PLM) tools are the digital backbone for the product data across its maturity states. This document focuses on the product engineering and associated aspects of the digital thread.

A. Reference Architecture

A technology agnostic connected digital thread reference architecture is described below

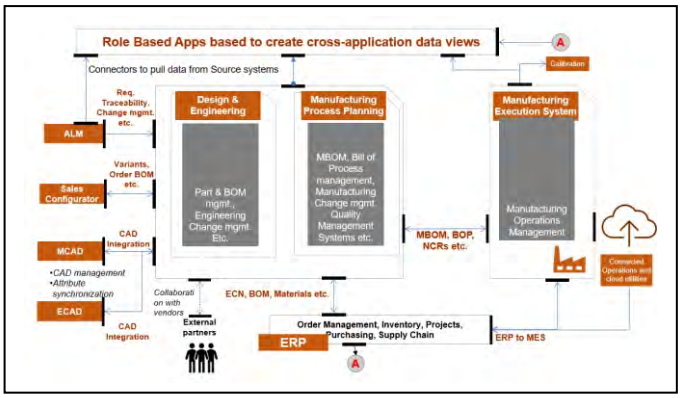

Figure 1 - Sample MBD model with PMI Information

B. Representative digital thread initiatives

A reference architecture detailing data ownership and data flows is an important aspect of solution development. As an .example, a representative digital thread across Sales, design & manufacturing is depicted in Figure 3

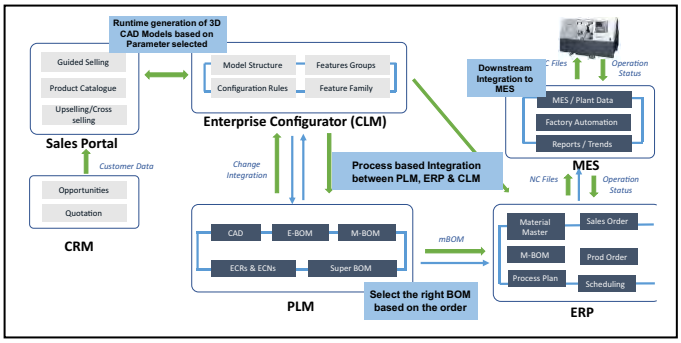

Figure 3 An example of a digital thread across sales, engineering & manufacturing

Global manufacturers can focus on high impact business specific areas to derive the most out of their digital thread investments. Some examples initiative are listed in Table 1

TABLE I.
REPRESENTATIVE DIGITAL THREAD DOMAINS

Domains	Representative digital thread initiatives	
	Benefits	Impacted business metrics
CPQ-Sales Configurator-PLM-MES	Streamlining Sales configurations across Sales, Design and Manufacturing domains	% of CTO orders versus ETO orders, Overhead Manufacturing Costs, Cost of Quality, Order Fulfillment Cycle Time, Design Reuse Frequency
PLM-ERP-MES	Sharing MBOM/Bill of Process with ERP & MES to enable integrated change Management.	Cost of Quality, Design Freeze to Job One Cycle Time, Order Fulfillment Cycle Time, First Time Through Quality, Manual Data Entry Reduction
ALM-PLM	Requirements traceability between ALM & PLM to enable integrated change Management.	% of Requirements met at Launch, Concept to Design Freeze Cycle Time, First Time Through Quality

IV. SOLUTION APPROACH AND ROADMAP

A digital thread links relevant information across the engineering applications based on business triggers. This increases complexity of the system and the resulting infrastructure as well as cost. To address these challenges, some of the foundational elements as well as approach are described in this section.

A. Best Practices

- It is essential to have a clear enterprise data model as a starting point. This entails having consistent definitions of items and their attributes across the ecosystem
- Identification of the value proposition driven by the relevant use cases. This is the first step towards prioritization of digital thread change initiatives and ensures that the effort and cost are expended towards the most profitable use

cases. Techniques such as "Value Realization Method" [1] helps create a line of sight between the key transformational metrics and the change initiatives

- Define clear ownership rules for items across user roles and systems
- Triggers for data transfers between applications based on lifecycle maturity stages especially for non-transactional data
- As a starting point, consider deploying mash-up based low-code tools like Mendix or ThingWorx to present contextual data across multiple applications
- And finally, the digital thread can only be effective if the underlying engineering data is consistent. A strong data governance along with cleansing should to precede the digital thread initiative to truly garner the benefits

B. Roadmap

Recommended approach to digital thread realization is to conceptualize the enterprise landscape and create an end-state view. The use-cases can then be built in a gradual manner prioritizing the value inherent in the use-case.

A typical digital thread journey of an enterprise is depicted in the graphic below.

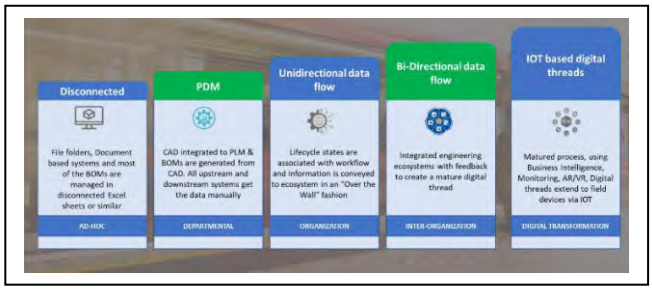

Figure 4 A representative maturity progression

The table below shows typical characteristics at each maturity level

Maturity Level	Typical characteristics
Disconnected systems	The EBOMs are manually created and are disconnected from the CAD design
Product Data Management (PDM)	Transfer of EBOM or MBOM to the ERP or shopfloor is manual
Uni-directional data flow	Integrations between PLM & ERP exists, and can transfer the BOM to the ERP system based on workflow-based approval triggers, or transfer of work instruction to the MES system post approval
Bi-Directional data-flow	- Shopfloor non-conformances and resulting design changes can be triggered thru the MES system (or) - Local inventory from the ERP systems can be visible to the design change coordinator to set the effectivity on an engineering change request before
IOT based digital threads	Field service agents can communicate with design engineering by sharing contextual real-time data on-line and even create a engineering change order or can trigger a field service notice to the individual devices on the field

V. REPRESENTATIVE OUTCOME

- Context - Electric equipment manufacturer, with highly complex configurable product having more than 1000 configurable parameters
- Problem Statement - Order to delivery process was manual, error prone and characterized by miscommunication causing delays
- Initiative - Creation of a digital thread across PLM, ERP, Sales Configurator, and shop floor to create an integrated configuration lifecycle management process
- Outcome – Reduction in “Time to Market” from 6 months to a few weeks [2]

VI. CONCLUSION

Product innovations are driven by seamless collaboration between domains of Software, Electrical, Mechanical & IoT to deliver personalized user experiences. With increasingly complex and technology driven products, Product Lifecycle Management is of paramount importance. Digital Thread encapsulates information and data sharing across lifecycle stages to ensure real time change propagation, collaboration amongst all the stake-holders and right first-time product delivery to ensure on-time New Product Introduction and meet enterprise level targets.

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ABBREVIATIONS AND ACRONYMS

PLM: Product Lifecycle Management
CAD: Computer-Aided Design
ERP: Enterprise Resource Planning software (like SAP)
NPI: New Product Introduction
MES: Manufacturing Execution System

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Demystifying Digital Twins: Example of EV battery twins to describe technologies and use cases

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Abstract -
Increasing use of virtual models during product development, as well as the adoption of service-oriented business models, have motivated the idea of building Digital Twins. Digital Twins are envisaged to be high-fidelity virtual models that can be used to study various aspects of a product without the need to access the actual physical product. A variety of solutions and approaches are being developed to establish digital twins in different industries. This paper presents a common framework, identifying the necessary components of any Digital Twin solution infrastructure. It also presents the case study of a Digital Twin infrastructure developed for EV batteries to demonstrate the utility of the proposed framework. This framework can serve as a baseline or reference architecture for building Digital Twin solutions. It can also facilitate the development of common standards for interfacing different components making it easier for companies to establish digital twin solution using the best combination of commercial and custom solutions.

Keywords - Digital Twin, IoT, framework, ML, Behavior Model, Electric Vehicles (EV), EV Fleet, Battery Life, Ride Analytics

I. INTRODUCTION

We are witnessing increasing use of virtual models during product design and development, arising from shortening product development cycles and increasing product complexity. With the adoption of service-oriented and solution-oriented business models, there is a growing demand for the use of virtual models even in the operational and maintenance phases of a product's lifecycle. The maturity of modeling and simulation technologies in 3D CAD models and Behavior models like CAE, multi-physics, co-simulation models, and Analytical/Statistical/Machine learning models, as well as emergence of technologies like smart sensors, Internet of Things (IoT), cloud computing, etc. have also contributed to this growing adoption.

This has given rise to an aspirational idea of a high-fidelity virtual representation acting as a Digital Twin, that can be used for any analysis in place of the actual product or solution. While there is general agreement on this aspiration, there is significant variety in the use cases foreseen by different industries and the approaches adopted by solution providers developing Digital Twin platforms and implementations.

In this paper, we will introduce a generic framework to help think about any Digital Twin implementation. The paper indicates how different Digital Twin implementations emerge from utilizing essential and optional components of the framework, and different technological variants for a component, depending upon the use cases desired.

The remainder of the paper is organized as follows. Section II describes some foundational concepts, taxonomy, and definitions that govern the discussion in this paper. Section III introduces the Digital Twin framework and its components. Section IV describes the deployment of Digital Twin infrastructure for an example case study of electric vehicle batteries, indicating the planned use cases, selection & development of different components in the framework. Section V

concludes the paper with a summary of the framework and its potential to develop Digital Twin implementations for various industries and domain specific use cases.

II. FUNCTIONAL CONCEPTS

The origin of the term "Digital Twin" is attributed to Michael Grieves and his work with John Vickers of NASA in 2003 [1]. A digital twin was envisaged as a virtual representation of a product, that stored information about a physical product (or process or system) and received data about the physical product, to mirror the state of the physical product. This drew upon parallels with NASA's practice of building physical twins at their facilities to simulate physical mechanical assemblies operating outside Earth's environment [2]. Since then, various studies and articles have been published building upon this idea in divergent ways.

Digital twins have been categorized in various ways depending on the criteria used. A common distinction is made between a "digital twin prototype" or "design twin" which is used in the development of the product (often even before a physical product is built), and a "digital twin instance" or "operational twin" that are used to represent individual physical products in operation [3]. Different studies have envisaged 3D CAD models as twins for visualization, simulation models as twins for performance prediction, dashboards and statistical/AI models for monitoring, maintenance, and diagnostics, etc. [4] Romina, et. al. [5] present a conceptual framework for digital twins. However, since they consider digital twins to be comprised of a set of models and data associated with a physical system, the framework focuses on the types of models and the different uses for twin, without focusing on the additional components required to establish the complete infrastructure to use the models.

Various digital twin solution platforms, such as "Predix" from GE, "Mindsphere" from Siemens, "Thingworx" from PTC, "Watson IoT Platform" from IBM, "Azure Digital Twins" from Microsoft, "AWS IoT TwinMaker" from Amazon, "Ansys Twin Builder" from Ansys, etc., are being advertised and provide different functionality and approaches to realize a digital twin solution. [6]

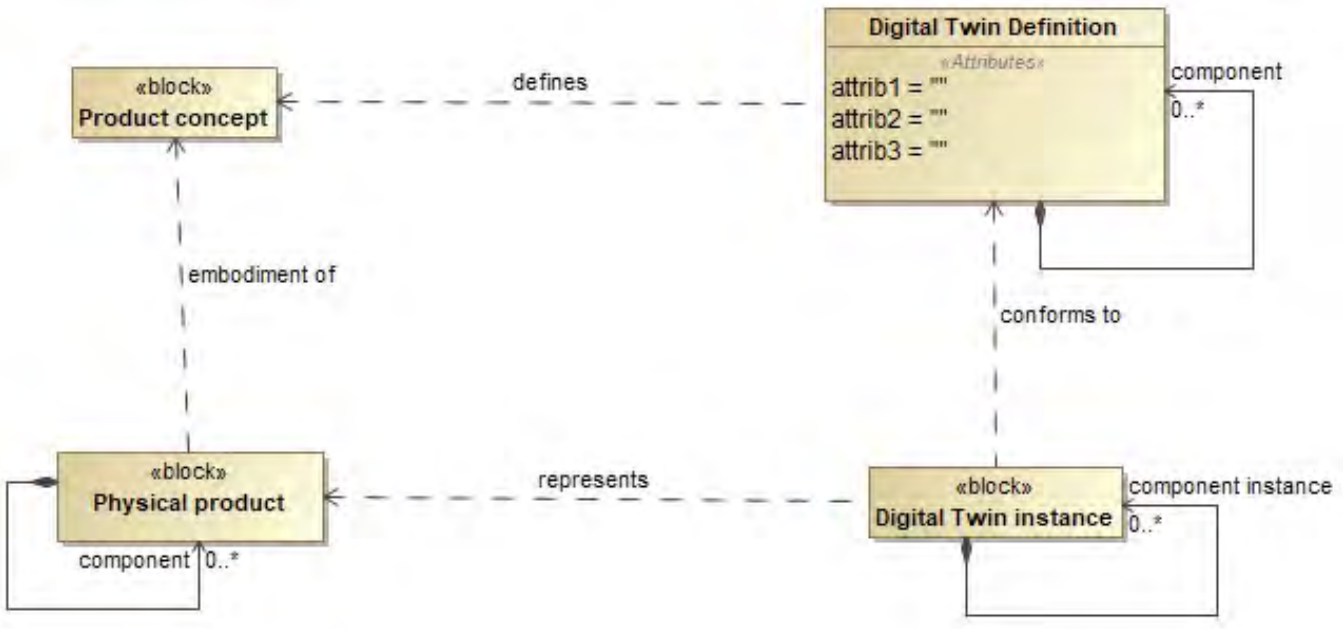

Figure 1: "Digital Twin Definition" and "Digital Twin Instance"

We consider a "model" to be an abstract representation of an object (or process or system). In many ways, "Digital Twins" are like digital/computer-based models. However, typical "Digital Twin" infrastructure involves various additional aspects, such as acquisition of data about the physical objects, storage and management of real time and historical data, aggregation of models from different domains, interfaces to enable specific use-cases, management of multiple twin instances, etc. This enables the Digital Twin instance to represent multiple aspects of the physical product, as well as mirror each aspect with greater specificity, such that it represents the specific physical product/asset (rather than a generic product class or category).

III. THE DIGITAL TWIN FRAMEWORK

In this paper, we shall describe the typical components, the roles they perform, and the interactions required between them, to establish and effectively use any typical "digital twin infrastructure".

Any Digital Twin infrastructure would have one or more "digital twin definitions". The "digital twin definition" essentially specifies the set of attributes that defines the properties and state of the physical product. These attributes may be simple values (e.g., mass), complex data structures (e.g., performance curves), and/or constraints and reference models (e.g., CAD, 1-D/3-D CAE model) in themselves. These attributes may be constant for the product class, updated at specific events (e.g., on the instantiation of the twin, or a maintenance event), sensed and updated in real time, or calculated in real time. The "digital twin definition" also defines the attributes for which historical values will be maintained. Such a definition is usually defined for every product, system, sub-system, that is relevant for the use cases being considered, and are often hierarchical with digital twins of any system being defined by a composition of digital twins of the sub-systems involved in addition to system level attributes. The Digital Twin Definition Language (DTDL) [7] is an emerging standard to specify such digital twin definitions. Thus, the Digital Twin infrastructure must have capabilities to create and manage (store, update, delete) such digital twin definitions.

The next component of any Digital Twin infrastructure is the set of digital twin instances. A digital twin instance is the entity that records and mirrors the state of a specific physical product (or process or system). Each digital twin instance conforms to the digital twin definition defined for

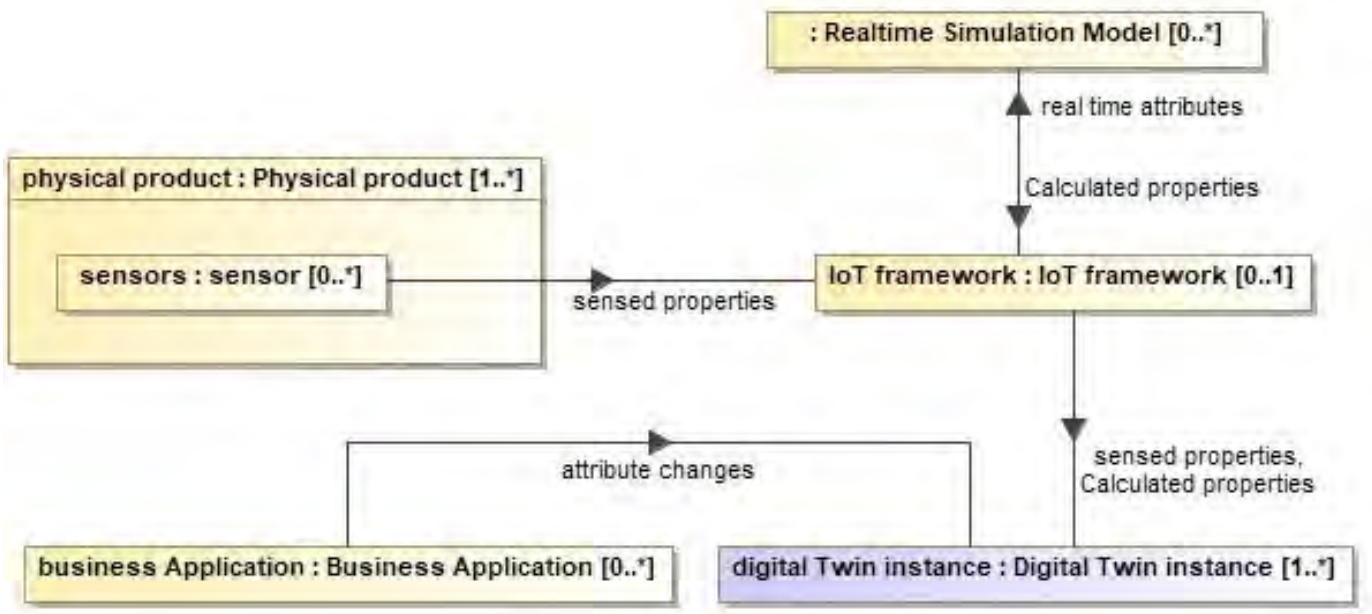

Figure 2: Schematic showing components and interactions to acquire data for digital twin instances

the product. Thus, a digital twin instance records some attributes of the specific product and may be composed of digital twin instances of sub-systems. Figure 1 shows the correspondence between a "digital twin definition", "digital twin instances" and the physical products. Any digital twin infrastructure must have mechanisms to create these digital twin instances, store current and historical states for these instances, and interact with these instances (read and write to attributes). The infrastructure may also have capabilities to trace to design models, or additional information about the specific product, or invoke evaluation models.

In order for the digital twin instance to accurately mirror the state of the physical product it represents; it is often necessary to acquire certain attributes directly from actual product in real time. Consequently, typical digital twin infrastructure will have sensors mounted on the physical products and mechanisms to stream the sensed information to the digital twin instance. Nowadays, this usually implies an IoT (Internet of Things) framework on the cloud that resolves individual streams from internet-enabled (smart) sensors and communicates them to the corresponding digital twin instance. However, often it might also imply networked sensors and on-board processing before the sensed information is communicated to the digital twin instance. Naturally, the digital twin infrastructure should support the capability to establish this correspondence between the individual sensor streams and the attribute on the specific digital twin instance.

The digital twin instance may also need inputs from other sources in order to mirror the state of the physical product correctly. For example, if a component is replaced during service, the digital configuration must be updated to reflect the new component. Thus, the digital twin infrastructure should also support establishing channels for different business applications (or external data sources) to update the digital twin instance.

Finally, some attributes of the digital twin instance cannot be measured or configured. They need to be calculated using models that will use other attributes of the digital twin instance as inputs. These models can range from simple equations, to complicated mathematical models that capture the physics that relates the attributes involved. These models can also be statistical models that infer the relationships between the attributes based on empirical data and/or machine learning algorithms. Since these models are instantiated for every twin instance and evaluated continuously in real time, we refer to such a model as "Realtime Simulation Model". The digital twin infrastructure should have the capability to establish channels

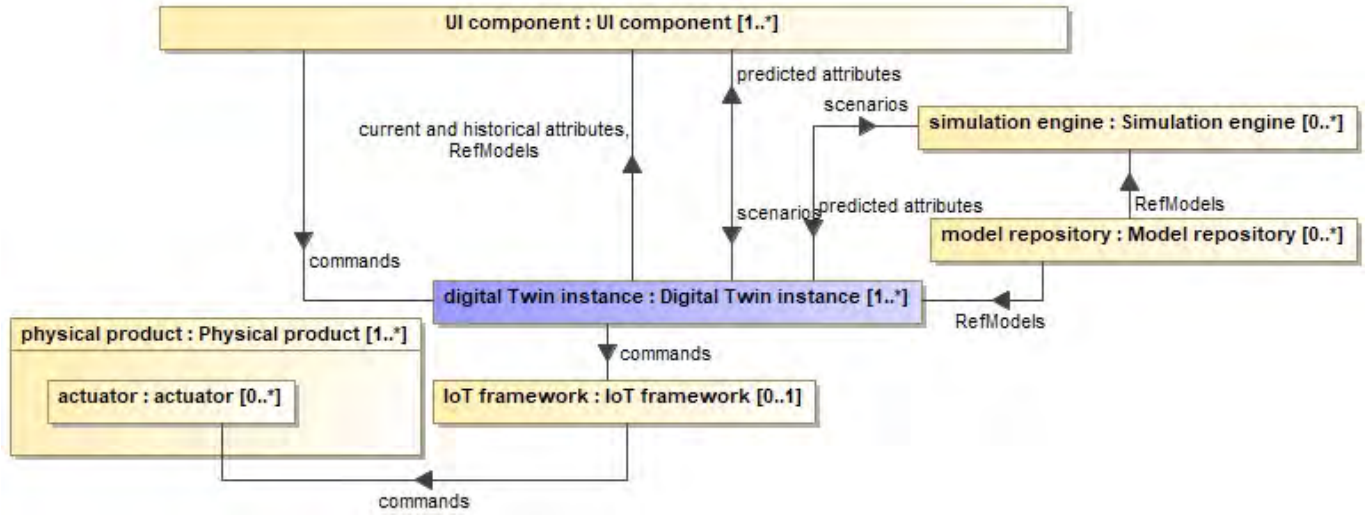

Figure 3: Schematic showing components and interactions required to enable different types of use-cases of digital twin

between the digital twin instance and the model evaluation engines to exchange the input attributes and resulting measured attributes.

All the components required for acquiring the attributes of the physical product and updating the corresponding digital twin instances are showing in Figure 2.

In addition to the components to create the digital twin instances and maintain them up to date, we also need components to use these digital twin instances. This usually takes the form of a web-based, interactive UI, where the user can browse through available digital twin instances and their hierarchy. But they can also be in the form of mobile apps, dashboards, or complex applications. If the use cases are mostly comprising of visualizing the current state, or looking at historical trends, the UI component needs to have the capability to fetch the digital twin instance data and present them to the user. These can be extended to provide alerts based on predefined conditions.

Some use cases require visualization of the state information overlayed on reference models, such as 3D CAD geometry, or layout diagrams, etc. In such cases, these reference models need to be associated with the digital twin instances before-hand, and the UI component should be able to query and retrieve the reference model and render the mode and the state information for consumption. For this purpose, the digital twin instance must record a reference to the model, which is usually managed in repositories. The digital twin infrastructure must provide the capability to interact with these model repositories and retrieve the right, configured model for the digital twin instance.

Some use cases will need the use of evaluation models to predict the state of the digital twin when subjected to some scenario or performance cycle. For such use cases, the digital twin infrastructure must be able to capture the scenario, assumptions, and boundary conditions from the user from the UI component and the current state of the digital twin instance as initial conditions. The infrastructure must have the capability to retrieve the relevant reference model from a model repository; host the execution of the model with given scenario, assumptions, and boundary conditions; and capture and transmit the results to the UI component.

Finally, some use cases require the user to be able to communicate and take actions on the physical product (e.g., switch off the physical product if it drifts to a dangerous state, or change settings on the product to optimize operation in anticipated conditions). For that the digital twin infrastructure must have the capability to establish communication between the UI component and the web-enabled (smart) actuators on the physical product. This will usually be mediated by the

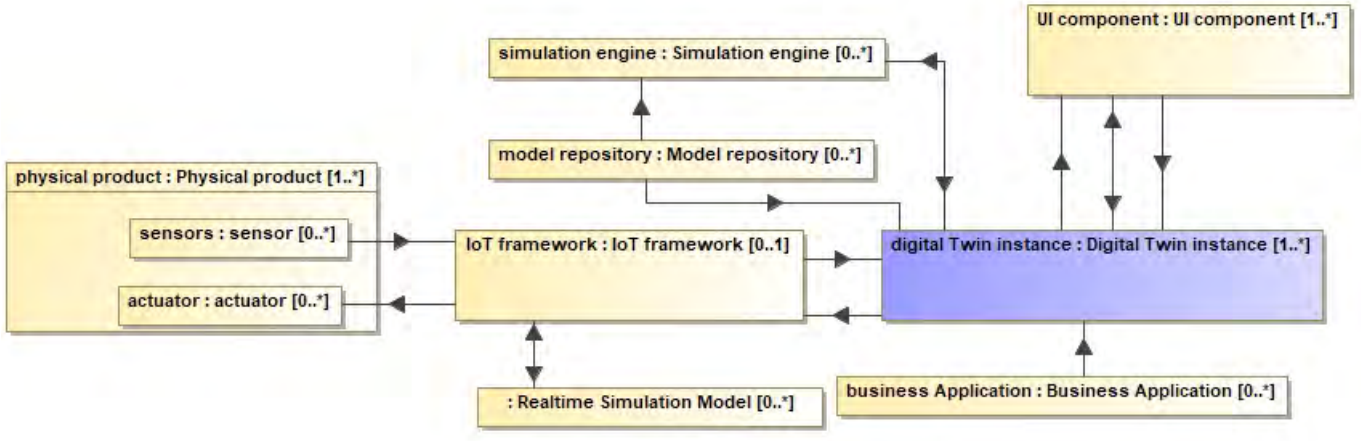

Figure 4: Schematic framework of functioning Digital Twin Infrastructure

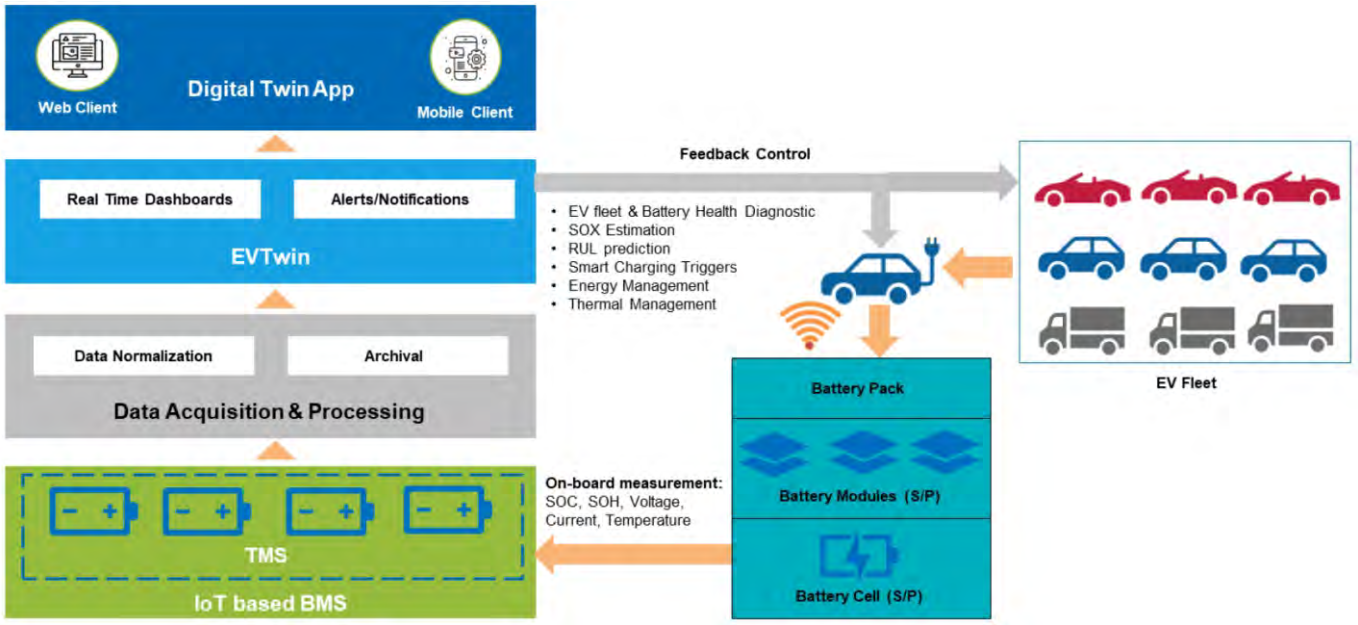

Figure 5: Conceptual representation of Digital Twin deployment for Electric Vehicle Batteries

digital twin instance and the IoT component to resolve the specific sensor that the actuation signal needs to be sent to.

Figure 3 shows a schematic of the components and interactions that may be employed to enable different use cases that are envisaged for the digital twin instances.

Figure 4 below shows the combined representation of all typical components of any digital twin infrastructure. Whether some of the components are included in a particular Digital Twin infrastructure deployment is largely governed by the current and future use cases that are envisaged. Note that this presents a conceptual view of the components involved. Depending upon the specific technologies and proprietary products employed for any of the components, additional components may be employed to achieve the functionality required.

IV. CASE STUDY FOR DEPLOYMENT OF DIGITAL TWIN INFRASTRUCTURE

In this section, we shall use the case study of electric vehicle batteries to provide an example of how the framework can be used to deploy Digital Twin infrastructure.

As shown in Figure 5, the broad vision is to have digital twin infrastructure to represent, monitor and optimize the use of batteries in a fleet of Electric vehicles. However, to scope the purpose of this case study let us consider that a supplier of electric vehicle batteries wishes to build digital twins to support needs of different stakeholders. These include:

- Track state-of-charge: Vehicle owners, especially fleet owners, would want to track the state-of-charge on the batteries in each vehicle of their fleet. This would be needed to schedule charging, manage load, etc.
- Track state-of-health: Battery manufacturers and service technicians would need to track the state-of-health of individual cells, modules, and the whole battery. This would help identify issues early and make early interventions to reduce maintenance and warranty costs. Moreover, this would also help battery manufacturers determine appropriate value for used batteries when they are bought back or employed for alternate (second life) uses.
- Receive hazardous state alerts: Both fleet owners and service technicians would like to receive alerts for emergency conditions, such as overheating, or failure of modules, etc. This can allow making quick interventions to prevent accidents.
- Track performance: Fleet owners would like to

track the efficiency of the battery, discharging rate trends based on load, etc. to identify and correct problematic driving behaviors. Battery would want to track performance of individual modules to characterize the performance of individual cells as well as control algorithms of the battery management systems.

- Track duty cycles and history: To improve battery manufacturers would also want to record historical trends in the loads and duty cycles, and the different machines.
- Predict performance for upcoming jobs: Fleet owners would also like to make optimal job allocations based on the current state of the available machines. Thus, the ability predicting behavior and parameters for different batteries in different vehicles for different routes, weather conditions, etc. would be of interest to them.

Based on the use cases identified, we deployed the components of the framework that would be necessary to enable them. Figure 6 shows the different commercially available or custom-built solutions that were used for the different components that were deployed. The role of the components is further described below.

A. Preparing digital twin definition and creating instances

As can be seen from the anticipated use cases, the digital twin instances need to represent different aspects and parameters of the battery at the cell level, module level, or the battery level. Hence, the digital twin definitions are prepared hierarchically, with cell digital twins being defined by cell level parameters, module twin being composed of multiple cell twins and module level parameters, and so on. The use cases would also require information about the vehicle the battery is installed in, and hence a minimal digital twin of the vehicle is also defined composing a battery and relevant parameter such as make, weight, reference to behavior models, etc.

For this paper, the digital twin definition was prepared on the Azure Digital Twins platform, using DTDL (or Digital Twin Definition Language). Digital twin instances were created hierarchically for a fleet of few different vehicles with different types of batteries. The digital twin instances, their configurations, etc. were maintained by connecting to an Azure Database.

B. Acquiring attributes of the physical products

For the example in this paper, we did not use physical products directly, but simulated the sensors and parameters of the physical product

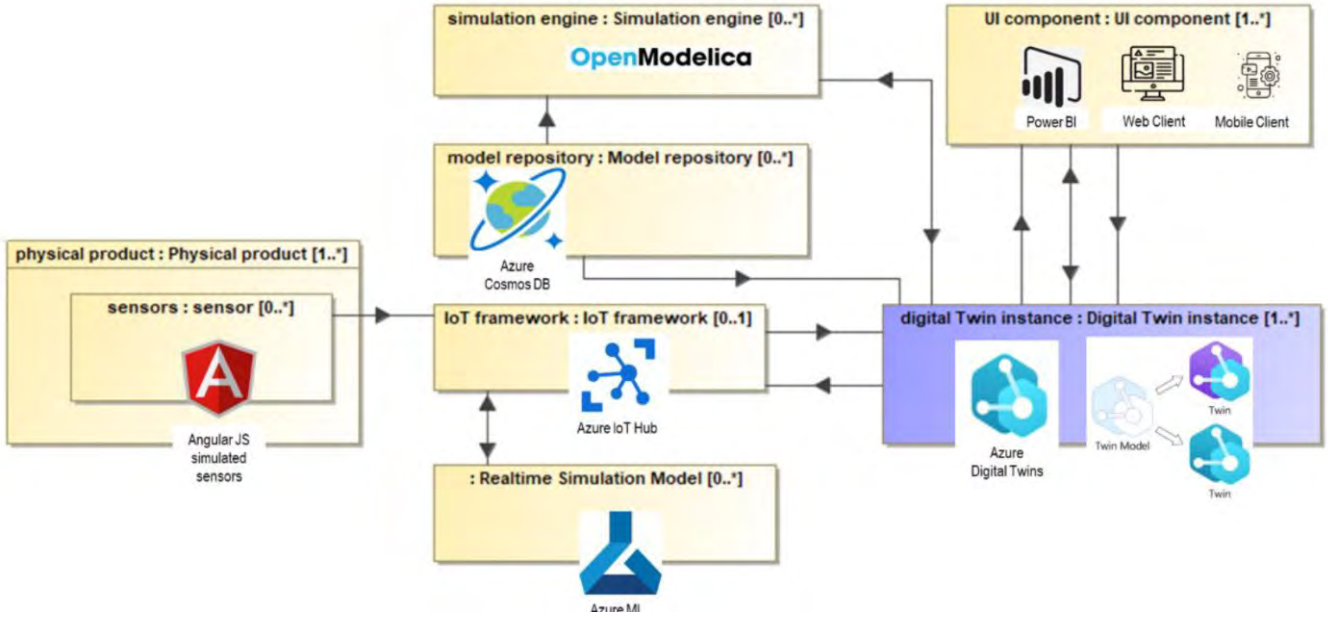

Figure 6: Components of the framework deployed for Case Study and solutions used

based on values and ranges observed in the past. Output streams for attributes, such as GPS location, speed, etc. for the vehicle; temperature, voltage, etc. for the battery pack; voltage, current, etc. for the individual cells; were simulated and streamed to an Azure IoT Central instance. Azure IoT provides the ability to manage each device/sensor stream. Azure functions were used to establish relations between the device streams and the Digital Twin instances.

C. Establishing connections with business applications

In this example, business applications were not integrated with the Digital Twin infrastructure.

D. Establishing virtual sensors

To establish virtual sensors, models to calculate the evaluated properties, such as calculation of State-of-Health based on voltage, current and temperature parameters, were established using historical data and Machine learning with Azure ML. Simple physics-based models, such as calculation of State-of-Charge, were also built. These models are included in Azure Stream Analytics, where the streams from the respective IoT devices were provided as inputs and model outputs were recorded to the respective digital twin instances using custom Azure functions.

V. CONCLUSION

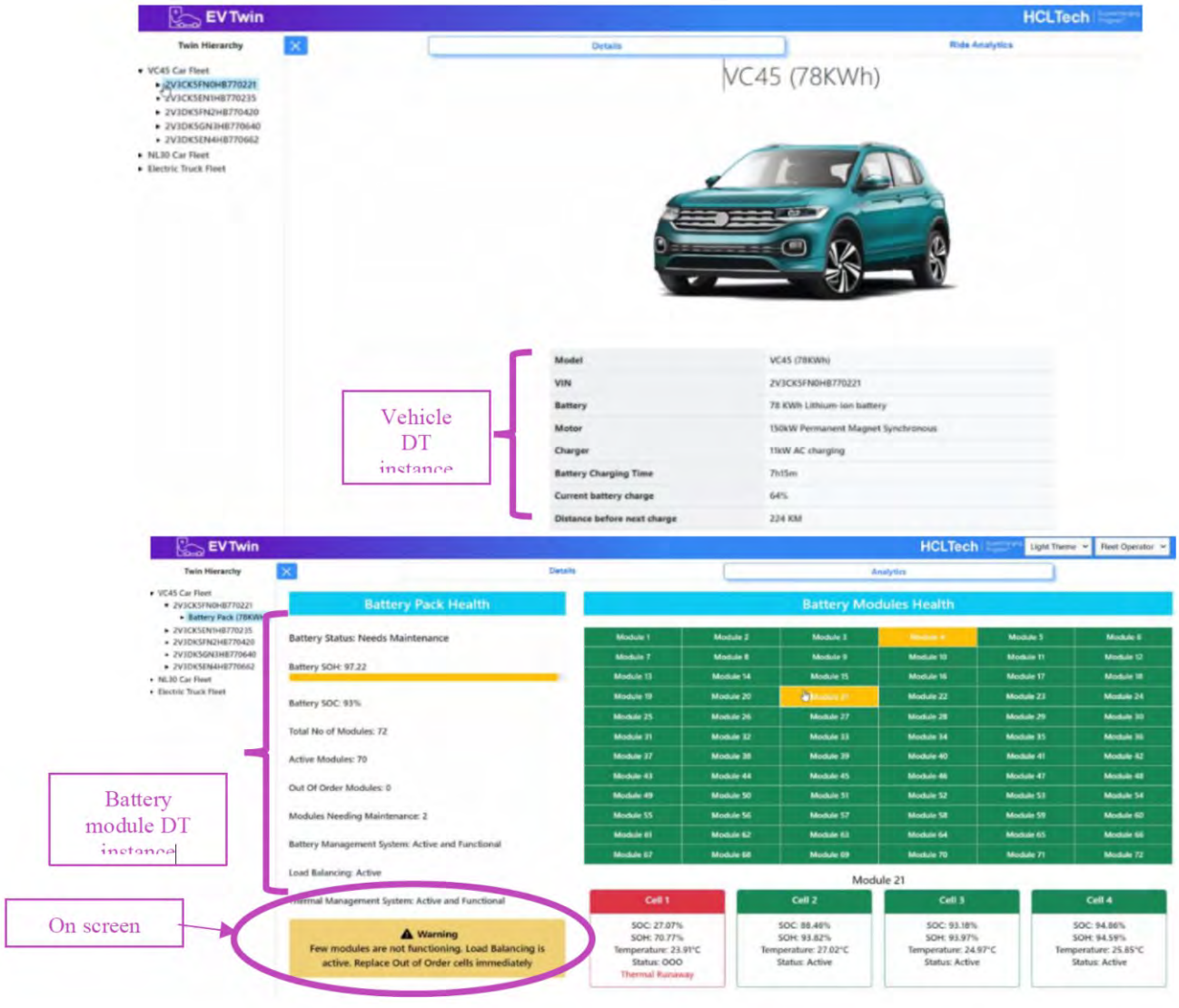

Figure 7: Webapp dashboards showing digital twin instance attributes at different levels of hierarchy

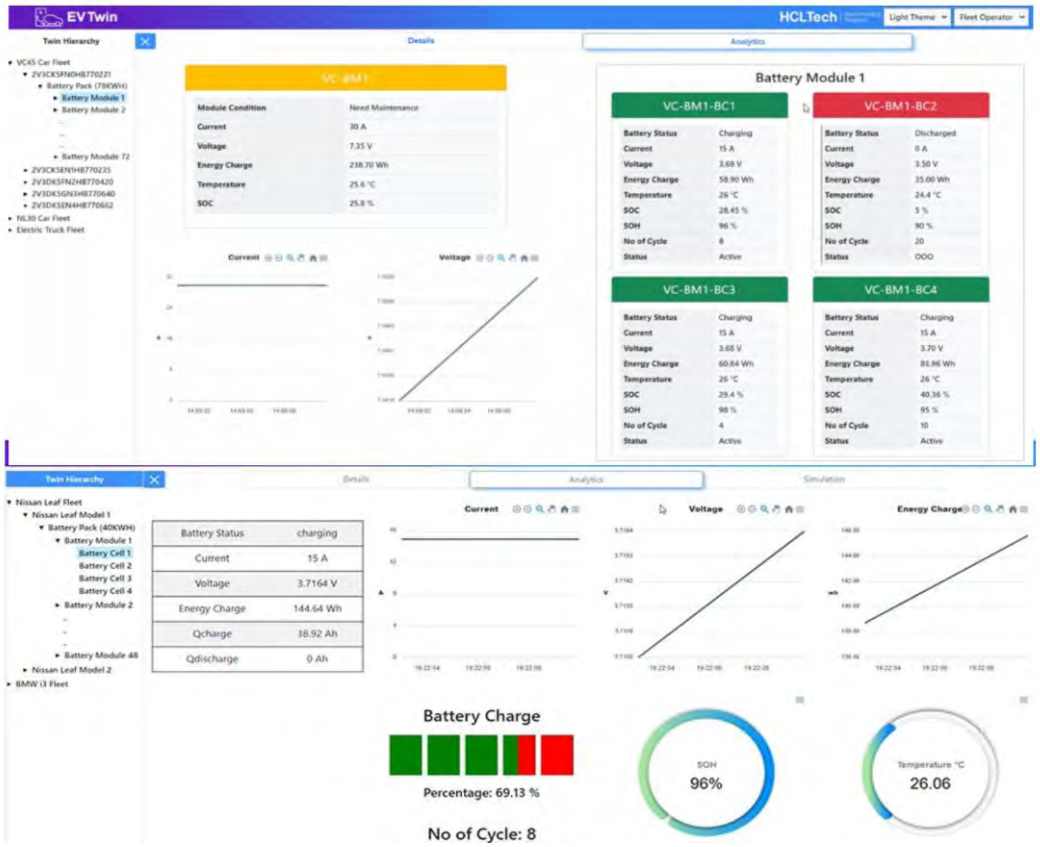

Figure 8: Webapp dashboards showing real time trends in parameters of digital twin instances at different levels of hierarchy

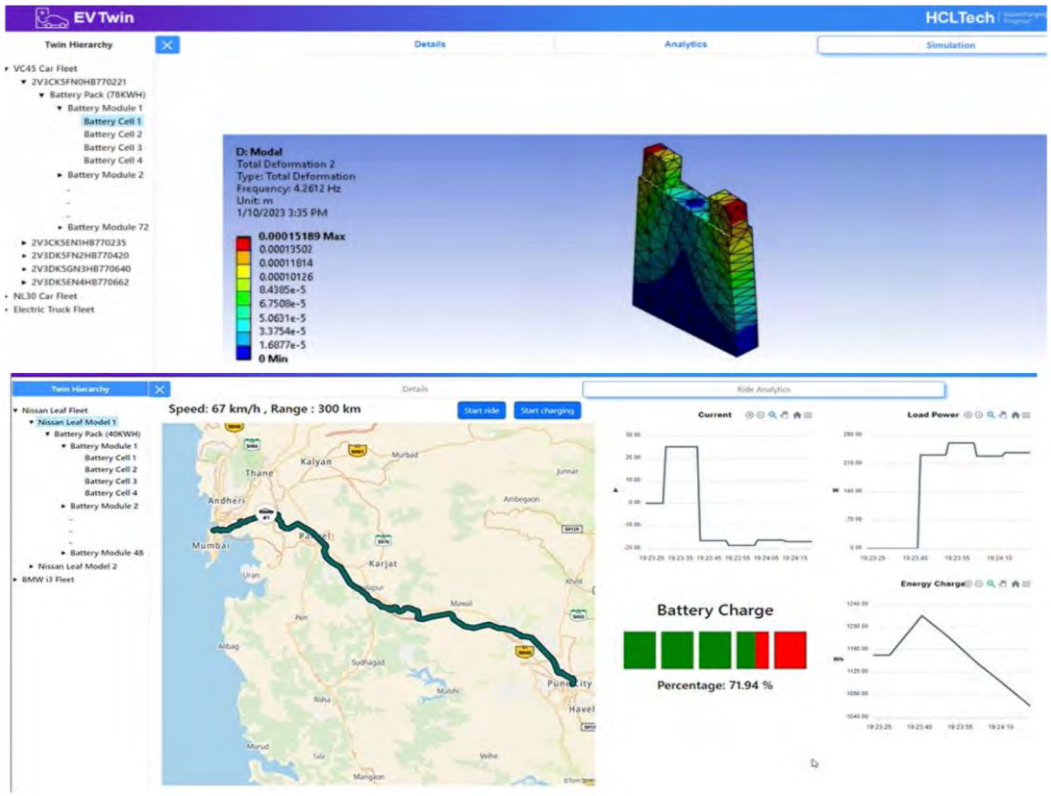

Figure 7: Webapp dashboards showing digital twin instance attributes at different levels of hierarchy

In this paper, we have presented a high-level framework for establishing digital twin infrastructure. The framework elaborates the components involved, and the relationships that need to be set up to realize the functionality required and satisfy the desired use cases. An example of using this framework for a specific case study is also presented.

We believe that this framework should help simplify the complex solutions and different approaches that are commercially available for deploying digital infrastructure. It can serve as a baseline to understand the components provided in the different commercial solutions and the additional efforts that might be needed to meet specific use cases of the organization. Furthermore, we expect that this framework facilitates the development of common standards for interfacing between different components and solutions and makes it easier for companies to build digital twin infrastructure using the best available combination of commercial and custom solutions.

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VIRTUAL TWIN TRANSFORMATION

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Abstract - The automotive industry is undergoing a transformation as it addresses the challenges of carbon neutrality, the electric mobility revolution, technological innovation, shifting user needs and habits, and the arrival of newcomers on the market. A pioneer in automotive industry, Renault Group launched RENAULuTion in 2020, a strategic plan to switch from volume to value strategy. Another objective is to move from a car company using tech to a tech company designing cars. As a tech company, Renault Group needs to be at the best level in term of Virtual Twin and hence launched in 2021 The RENAULuTion Virtual Twin (RVT), a cross company transformation program to build and manage product lifecycle in every business lines. A virtual twin is a digital model designed to accurately reflect a physical product. RVT is a practical version of "Digital twin" concept developed with business-oriented functionalities with an intension to share all data related to the product & services throughout its life cycle and to establish an only source of truth for all departments across the organization.

Keywords - Renault Group, Digital Strategy, RENAULuTion Virtual Twin (RVT), Backbone, Digital Twin, PLM, Dassault Systèmes, Software Defined Vehicles (SDV), original equipment manufacturer (OEM).

I. INTRODUCTION

The goal of Renault Group's RENAULuTion Virtual Twin (RVT) program is to create and enable the next revolution in automotive workspace. Product lifecycle management (PLM) has been a staple in development of new products in a sustainable and integrated manner. One of the main goals of RVT is to revolutionize the PLM approach to influence all its aspects including internal processes & collaboration, associated technologies, and management of products across its lifecycle.

The choice of an optimal PLM tool is crucial for the OEM considering that it must satisfy both short- and long-term objectives. These objectives are tied with several constraints including intrusive collaborative platform and issues concerning data quality, architecture mismatch and irrelevant Out-of-the-box (OOTB) solution. The varying nature of these issues necessitates the evaluation of several engineering processes and development of functionalities that supports the team integration and deployment.

With over two decades of extensive collaboration, Dassault Systèmes has contributed to Renault Group's growth and development. As part of the latest PLM solution, Dassault Systèmes has proposed the development of the Virtual Twin for exactly mimicking the real-world products of Renault Group. The Virtual Twin is a breakthrough

innovation to accelerate the digital transformation of Renault Group. To customize this concept, RVT builds the new level of PLM system in its pure meaning. RVT acts as the collaborative backbone of product digital data management, which would ensure acceleration of cross-team collaboration and product creation from conceptualization to final release. Apart from cross team collaboration within the organization, RVT serves as an effective platform to include business partners with its extended enterprises capabilities.

II. DEVELOPING A PLM SOLUTION

A. How PLM works?

PLM tool-based processes enable standardization of product development to design, industrialize, manufacture, and maintain new products, aiming towards more efficiency, collaboration, and sustainability when released to the market. For each department in the organization, a PLM tool must provide access to the latest product information when needed as per the requirement of individual teams [1].

PLM eliminates waste and improves efficiency across all aspects of a product's life--from initial requirements to deployment and resolving constraints for manufacturing readiness. By deploying people, product information, processes, and technology to optimize time, energy, and material across an organization into the supply chain, PLM drives the next generation of lean thinking [2].

The expected outcome of the process is to supply engineering and operational process actors and their clients (After sales, Purchasing, Simulation, Perceived quality...) of vehicles and mechanical projects with the Digital Prototypes and their associated data to perform a wide range of objective based activity.

B. Product lifecycle's phases

While Product Lifecycle Management can be intended as a business strategy, the main phases of product lifecycle involve design, development, and maintenance of the product. In addition, it involves allied transversal actions such as sharing, process automation, acceleration of product development methods, improved communication among teams and partners, capitalization of information and latent knowledge [3].

C. Evolution of PLM

Sometime around the mid-1960s, Computer-Aided Design (CAD) systems evolved to provide further capability than mere reproduction of manual drafting with electronic drafting resulting in cost-benefit for companies to switch to CAD [4]. Successive CAD systems provided enhanced features and functionality. Although primarily associated with detailed engineering of 3D models or 2D drawings of physical components, CAD has also been applied through entire engineering processes from conceptual design and layout of products to strength and dynamic analysis of assemblies and defining manufacturing methods of components. In parallel with the development of Computer–Aided Design, Manufacturing and Engineering (CAD/CAM/CAE) tools, Product Data Management (PDM) systems appeared around the 1980s to control and manage the "ever growing" product information created by various PLM processes & tools [5].

The need for easy, fast, and secure access to valid data during the product design process was the major drive for development of PLM tools. The core functionality of early PLM tools was to provide users with required data through their central data repository and ensure integrity of the product data with sharp management and control of data lifecycle.

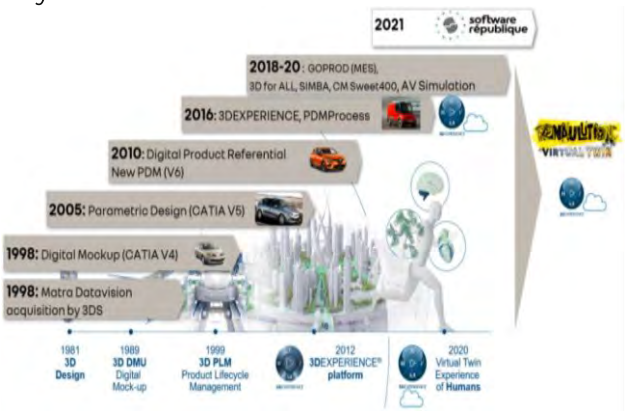

Fig. 1. Evolution of PLM systems in Renault Group

In course, PLM solutions were supplemented with new functionalities like change management, document management, workflow management and project management that promised concurrent engineering and streamlined product development processes within the enterprise.

D. Challenges of PLM

One of the fundamental challenges plaguing every manufacturer, and which PLM aims to solve, is the isolation of essential information. With numerous teams involved in the production process, the need for a solution that enables every concerned individual to access relevant data is of paramount importance. Overlooking this usually results in premature launch of certain product tasks, leading to under-utilization of resources and wastage. This is also accompanied by systemic non-cooperation among various teams owing to lack of communication.

As in [6], the product's complexity is increasing over time, the ways and means of the PLM must maintain the same level of easiness of access and collaboration to more and more data, for different needs, depending on:

- business perspective: each department need different data or aggregation level
- level of maturity of the product: data may be partial, in construction
- user intention: viewer, updater, creator of new data

To overcome this challenge, PLM systems should provide standards to ensure convergence of all this "viewing angles" but also be flexible to allow specific activities to create their own workbench, to adapt to their specific process. For the OEM process, product complexity increased in so many different directions, all driven by cutting-edge technologies. Here's a non-exhaustive list:

- Advance Driver Assistance Systems (ADAS)
- Engine continuous improvement and diversity (thermal, electric, hybrid, H2)
- Onboarded entertainment systems
- Sustainability improvements (product and manufacturing)
- Security improvements.

To be able to extend and improve the product functionalities and reliability as well as the manufacturing and supply chain contingencies, job lines changed and adapted, with PLM help to cope with it. And it is not easy to implement. As always with heavily digitized process, the tools and process have an influence on each other and evolve together. Modelling the organization, the process and building a proper data model for the PLM to insert into the Information System is a process by itself. Many issues may arise from a weak or incomplete model [7].

III. FUTURE OF PLM TECHNOLOGY

Some of the near future trends and opportunities for PLM technology are Digital twin, Blockchain, Augmented and virtual reality (AR and VR) [8]. One of the key technologies is Cloud deployment that can help PLM technology to increase scalability, flexibility, and accessibility of product data and processes. AI is another emerging technology that can have a significant impact on PLM technology [9].

ANN ARBOR, Michigan, USA 23 August 2022 — CIMdata, Inc., the leading global PLM strategic management consulting and research firm, announced the release of the CIMdata PLM Industry Analysis Report, the fifth of five modules of the CIMdata 2022 PLM Market Analysis Report Series [10]. The MAR Series provides detailed information and in-depth analysis of the worldwide PLM market during 2021. It contains analyses of major trends and issues, revenues of leading PLM providers, and revenue analyses for geographical regions, industry sectors, and historical and projected data on market growth. All industries exhibited growth in Mainstream PLM spending in 2021, as shown in the Fig. 2 (PLM Spendings in 2021) below. CIMdata forecasts have maintained growth in all industries during the five-year forecast period.

As seen from the bar chart, PLM spending is highly focused on automotive and other modes of transportation, mechanical machinery and heavy equipment and aerospace & defense. The crux of this spending involves product innovation,

operational excellence, and customer intimacy, which will lead to competitive differentiation. To achieve this on a continual basis, it is important to devolve the expenditure on PLM from purely engineering challenges and aim for an integrated approach involving all organizational departments [11].

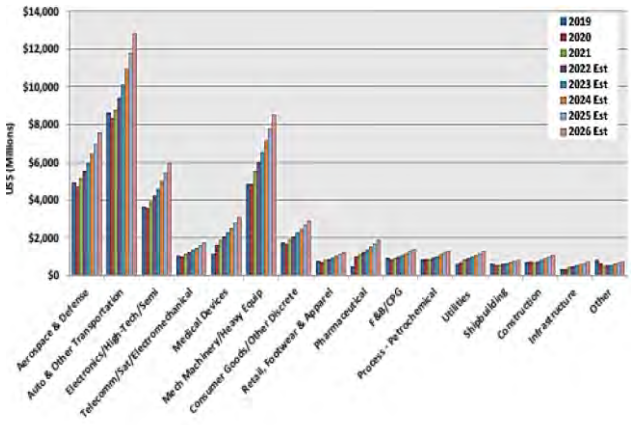

Fig. 2. PLM Spendings in 2021

IV. RENAULUTION VIRTUAL TWIN: NEXT-GEN PLM

RVT goes one step further to build an extended enterprise solution, ensuring all stakeholders including suppliers, partners, Aftersales, Purchasing, Costing, Quality etc. collaboration through a common platform. It allows the right access to each user based on their needs, with a strong management of configurations. RVT is also a collaborative backbone to manage upstream data and built around three pillars:

1. Robust & Agile Product/Process Manufacturing Design
2. Transformation in Systems & Software
3. Collaboration & Data.

Fig. 3. From Engineering to Enterprises platform - RVT

As shown in Fig. 3 the key objective for Renault Group to develop RVT is to switch from an Engineering Digital mock-up PDM to a Global Cross Company Collaborative platform deployed in cloud to accelerate the product development.

V. THREE PILLARS OF RENAULUTION VIRTUAL TWIN

RVT (RENAULuTion Virtual Twin) is a Collaborative Backbone to share all product data & services throughout its life cycle thereby acting as a unique source of truth. The goal of RVT program is to suppress silos and aid in switching from an engineering to a cross company Virtual Twin & PLM in addition to managing access to data sourced from all Business Lines.

The chief advantage of RVT lies in its holistic approach spanning from product conceptualization. RVT can manage design methodology and analyses as well as allied processes that would result in a physical product significantly ahead of actual realization. RVT allows efficient collaboration to facilitate sustainable product development. RVT is a next-gen PLM platform, made of 100+ initiatives involving all departments allowing an agile deployment of the solution and possessing three verticals as shown in

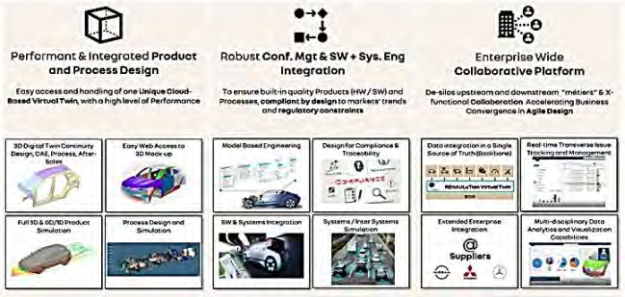

Fig. 4. Three pillars of RENAULuTion Virtual Twin

A. Performant & Integrated Product and Process Design

The mean time required to unveil a new car model is around four years with a significant fraction (> 50%) of this duration being engaged in complete digital development. Subsequent timelines are concerned with development of the first physical prototype which involves huge investment in

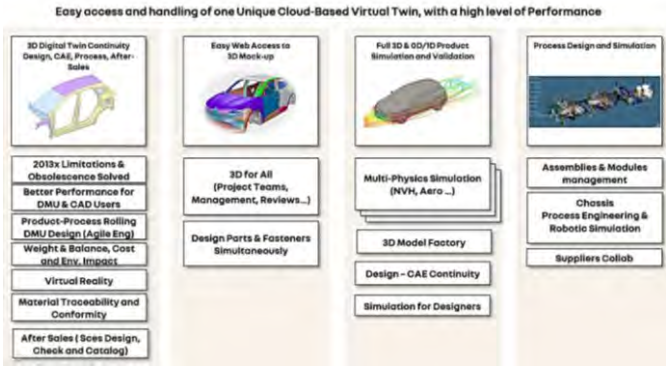

Fig. 5. Initiatives of Integrated product / process design

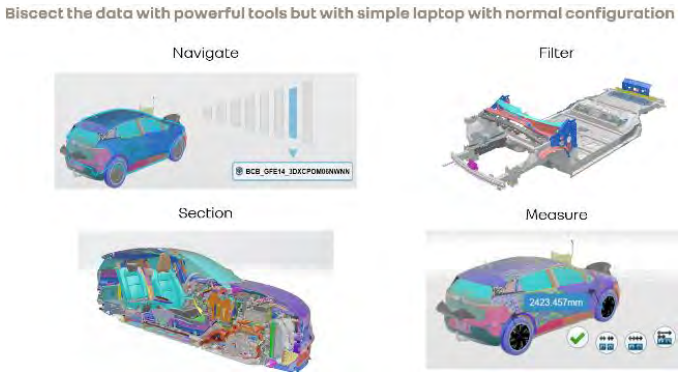

Fig. 6. 3D for All – Key functions

tooling. In this regard, the Integrated Product Process Design (IPPD) ensures that the requirements of the customers and those who deliver the product through both manufacturing and outside procurement are considered at the beginning of the design/build cycle [12]. Thus, the first pillar of RVT contributes to a robust & agile product/process design.

RVT combines the product design with process design to create a new standard for producing competitive and high-quality products. Pillar one comprises the following initiatives (as shown in Fig. 5): Robust Product / Process Design: Agile Product Process Design, 3D for All (as shown in Fig. 6), Virtual Reality, Material Traceability and Conformity, After Sales (Design, Check and Catalog), Fasteners, Multi-Physics

Simulation (NVH, Aero ...), Model Factory, CAE-Design Continuity, Simulation for Designer, Robotic Simulation, Supplier Collaboration.

The chief outcome from Pillar 1 is easy access and handling of Unique Cloud-Based Virtual Twin with high performance. A key desirable is in providing 3D mockup access to everyone (Engineering, Suppliers, Quality, Purchase, Costing, Manufacturing, etc.....) that allows for exploitation of the digital mockup.

The range of every vehicle of the Renault Group is made available in the cloud to be accessed by all stakeholders within the organization with minimal resources.

B. Robust Conf. Mgt & SW + Sys. Eng Integration

Systems engineering ensures integration of project aspects of a project or system. It deploys a host of tools including model-based simulation, requirement analysis, and scheduling to manage complexity [13]. In the automobile industry, a robust System Engineering in combination with Configuration Management enables the OEMs to manage higher complexity and to enforce regulation compliance with system traceability (Fig. 7) from product requirement to validation and until certification.

Considering that digital integration is vital for a project having several dependencies, the aim of RVT's is to provide a platform with conventional methods to administer concurrent engineering and multi partnership contexts with configuration also being a part of the virtual product integration. RENAULuTion Virtual Twin platform allows the users to establish and execute collaborative reviews with the common set of CAD & metadata. The resultant digital reviews would result in potential reduction of non-productive iterations.

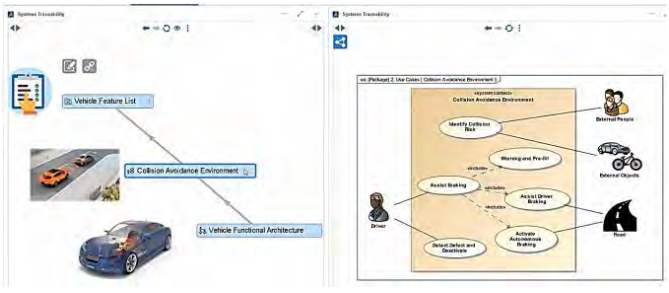

Fig. 7. Systems traceability – RVT

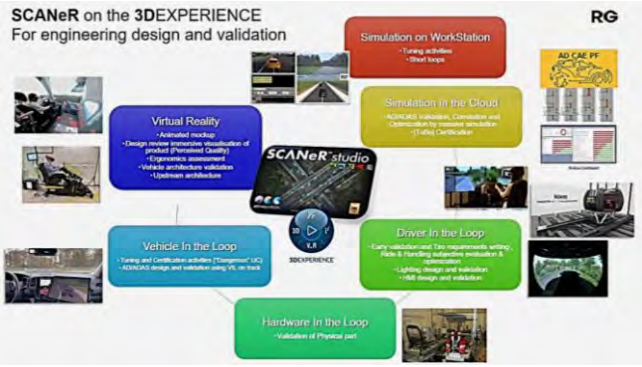

Fig. 8. SCANeR integration with 3DX - RVT

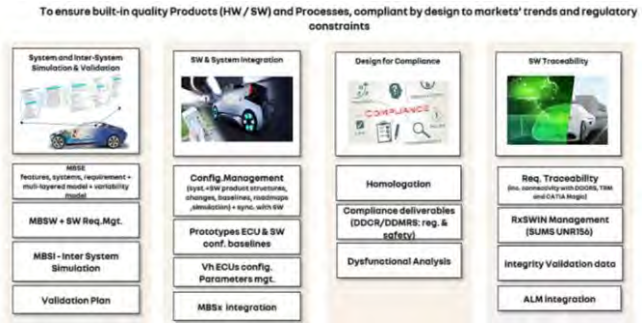

Fig. 9. Initiatives of Conf. Mgt & SW + Sys. Eng Integration

Renault Group's products have evolved to higher complexity owing to connected, autonomous and electrified vehicles. Along with Dassault Systèmes, they have developed a solution to engineer autonomous systems by integrating SCANeR (as shown in Fig. 8), an advanced driving simulator with 3D Experience(3DX). This integration forms the foundation of the compliance aspect of the RENAULuTion Virtual Twin. The digital chain based on SCANeR as an orchestrator with 3DX for virtual twin management is the key to design and validate complex systems. The advanced driving simulators execute and process computationally extensive simulations of several possible autonomous driving scenarios over cloud. These simulations involve validation software and encompass domains viz. headlight, sensors, traffic, and compute features that empower the validation team to drive millions of realistic virtual miles. The workflow enforces a digital thread by utilizing reusable scenarios as well utilizing various vehicle models. It is used in an Agile framework for verification and validation with a digital platform at all phases of the project.

This powerful system provides the platform for the automobile OEM to develop and maintain Software Defined Vehicles (SDV). The centralized architecture makes it possible to update and integrate new applications to enhance the vehicle functions. In addition, it also creates traceability to run baselined simulations and as a result, this new integrated system facilitates significant advancement in the efforts from early development phase to digital in reducing prototyping by over 50% in expenditure. Following this, Pillar two comprises the following initiatives (as shown above in Fig. 9): Mastering Systems/Software: MBSE (Model Based System Engineering), MBSI Inter System Simulation, Validation Plan, Configuration Management, Software Defined Vehicle, SW Traceability, Compliance deliverables, Homologation files, ALM integration.

C. Data & Enterprise-Wide Collaborative Platform

To enhance the collaboration of the OEM teams with our working partners and suppliers, Renault Group has engineered an enterprise-wide synergic platform known as XVT (eXtended Virtual Twin). This is a part of the RENAULuTion Virtual Twin Program (RVT). XVT is a module designed to shape Renault Group's business domains with the 3DEXPERIENCE platform. Specifically, the XVT module enriches the Digital Mock-Up visualization (3D4ALL) using data derived from our legacy information systems across multiple business domains including Engineering, Purchasing, Costing, Quality, and others. The XVT module employs Business Intelligence (BI) technologies coupled with 3D visualization to improve collaboration within these domains and support

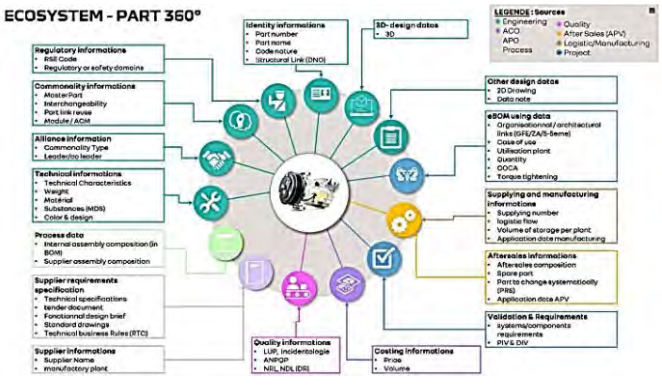

Fig. 11. Part 360 – One place to find all information

the design / validation / series process of Renault Group's Engineering.

Pillar three comprises the following initiatives (as shown in Fig.10): Data & Collaboration: Agile Engineering, Collaboration, Project Management, Part360, eBOM management, Document Management & Traceability, Market Intelligence, Supplier collaboration, Business Intelligence.

To elucidate the effectiveness of the XVT platform, we discuss "Part 360" (refer Fig. 11), a data perspective created within the framework of XVT platform. The aim of Part 360 is to share the largest possible part data panel with its user.

VI. WHY RVT & HOW TO SUSTAIN?

The digital model is the core of the RVT program (RENAULuTion Virtual Twin). It is designed and expected to manage all digital models of mechanical components and vehicles in a tool accessible to the various business lines of the company. Apart from providing a virtual replica of the product, the RVT comprises a powerful algorithm that can determine a car's features namely- handling quality, aerodynamics, test on-board safety equipment and aids to replicate realistic road test simulations.

The resultant collaborative platform (Fig. 12) provides solutions to address the challenges faced by the Automotive industry namely Exponential Growth of complexity with Systems, Development of Software Defined Vehicles (SDV), New Regulation constraint and requirement of robust traceability.

Fig. 12. Develop, test & Improve – Common Data

A. How to sustain

Renault Group has been practicing Agility at scale since 2018, strongly inspired by SAFe methodology and tailor-made to the requirements of the organization. Renault Group's team have applied prior learning experience to engineer RVT which is proposed to be an inclusive platform that allows the teams to collaborate on whole product development by utilizing a common database. RVT is a composite result of 100+ autonomous yet interrelated initiatives proposed by each department of the organization with an objective to significantly increment value addition and development planning. RENAULuTion Virtual Twin (RVT) is a program planned over 5 years (2021-2025), with a clear focus on delivering different modular objectives every year with focus on delivery value to end users of the solution and more transversally to Renault Group. The sustainability of the program is ensured through phase-by-phase deployment, which is precisely aligned with the aim of value creation, as in [14] (refer Fig.13).B. Benefits

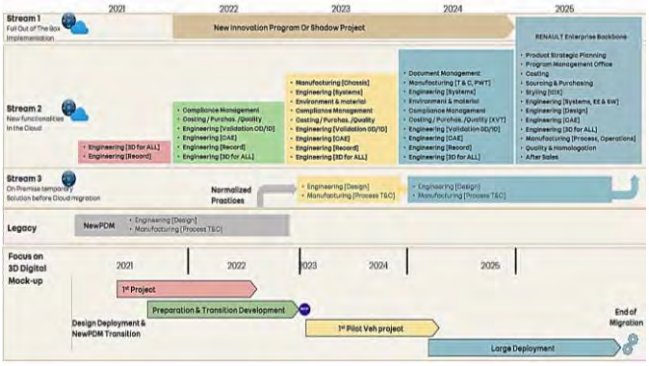

Fig. 13. RVT – Value streams

As explained earlier in Section III, Since Automobile OEMs are the top spenders in PLM solution, Renault Group is expecting great value from their digital strategy.

The outcome of RVT for Renault Group is to reduce costs with less expensive prototypes by performing more digital simulation and less physical testing, improve quality of design to be right first time with less modifications after digital phase and finally, contribute to time to market with a reduction of project lead time. B.

Fig. 14. RVT – Engineering performance contribution

VII. BUSINESS INTELLIGENCE

The ultimate goal of BI initiatives is to drive better business decisions. To achieve that goal, BI incorporates a combination of analytics, data management and reporting tools, plus various methodologies for managing and analysing data that enable organizations to increase revenue, improve operational efficiency and gain competitive advantages over business rivals.

RVT comprises an Information Intelligence app that provides visual dashboarding of critical information. By revealing key information, it enables you to make decisions based upon multi-criteria data analysis on a scale ranging from global to precise. Our solutions transform large volumes of heterogeneous, multi-source data into meaningful, real-time information intelligence to help users make informed decisions that improve business processes and secure competitive advantage.

VIII. CONCLUSION

Nowadays, the automotive industry is facing several challenges:

- New business expansion and new areas to be addressed, especially around software development, data monetization & services through strategic digital plan.
- New regulations and constraints for quality and sustainability
- Financial constraints due to margin reduction and raw material variations
- Higher degree of uncertainty pushing to deliver solutions faster

In this context, Renault Group chose to put in place RENAULuTion Virtual Twin, its new enterprise wide referential for product lifecycle management, putting the digitization to a new threshold in terms of:

- **Efficiency:** Lead time and costs reduction obtained through direct collaboration for the Extended Enterprise and accuracy of data within the shared "Single source of truth"
- **Innovation:** New technologies and best of breed digital tooling are used to produce best class new vehicles, bringing the simulation to another level with integration of 0D/1D simulation and more models including onboarded software
- **Quality:** Automation of controls and traceability allow both to speed up vehicles program and regulatory requirements
- Scalability: with the 3DX technology and the cloud hosting, inclusion of new functional domain is easier and faster

RVT is a strategic asset that will support Renault Group in the industry challenges for the years to come.

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Prediction of remaining useful life of AMAGB gearbox based on digital twin concept: A Survey

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Abstract - Aircraft Mounted Accessory Gear Box (AMAGB) is a high speed gearbox mounted on fighter aircraft. It takes input from engine through PTO shaft and drives other accessory systems of the aircraft. The functionality of gearbox is critical for proper functioning of subsystems associated with the gearbox. Thus it is essential to monitor running state and predict remaining useful life (RUL) of gearbox on real-time basis. In this paper, Digital Twin concept is employed to predict RUL of gearbox. Various factors that affect the life of gearbox are discussed. Workflow to predict RUL based on real-time data has been presented.

Keywords - AMAGB, Digital Twin, failure modes, real-time data, RUL, virtual entity

I. INTRODUCTION

Aircraft Mounted Accessory Gear Box (AMAGB) is a heavy duty, light weight, high speed and compact gear box of fighter aircraft. The main purpose of gear box is to drive the aircraft accessories which includes hydraulic pumps and drive generator. This Gearbox is driven by N20 engine through Power take-Off (PTO) shaft and it can operate at speeds up to 16,810 rpm. The Gear box operates in two modes, starting mode and normal operating mode. In the starting mode, Jet Fuel Starter mounted on gear box gives the starting drive to engine. When the normal operating speed of engine is attained, Jet fuel starter gear gets disengaged from Power Take-Off Shaft (PTO) shaft and the gear box starts to drive accessory systems of aircraft through power received from engine. The salient features of gear box are listed below [1].

1. The casings of gearbox are made of light weight Magnesium Alloy.
2. Spur gears are designed as per DIN5 standard and mounted on the shaft through ball bearing.
3. Self-contained lubrication system with integrated tank which is designed to operate satisfactorily up to altitude of 16 km.
4. High speed starter gear train to transmit high staring torque of 370 kgf-m.
5. Gear train with sufficient strength designed for power transmission up to 185 kW.
6. Gear train have been tested up to speed of 18,000 rpm and can run up to 21,000 rpm.

It is important to ensure normal functioning of the gear box at all operating conditions. If any component of the gear box fails or start to malfunction, this will lead to failure of the accessory systems

which in turn subsequently affect the operation of engine and other major systems. So it becomes important to assess RUL on real time basis, monitor & predict the health of system so that failures of sub-systems could be predicted. Presently CVRDE uses deterministic simulation methods and experimentation to predict life. RUL of gearbox needs to be predicted considering health of all components. This give closer estimate of the life of gearbox. Currently, digital twin technology is finding widespread application in predicting RUL of mechanical system based on real-time data. CVRDE is interested in developing a digital twin, to predict the life of gear boxes. Digital twin is a virtual representation of a physical entity. The digital twin model is continuously updated with real-time data from sensors installed on the physical entity, and this allows users to study and monitor the performance of product during actual operating conditions. This is done using advanced technologies like Cloud Computing, Artificial Intelligence (AI), Machine learning and Deep Learning algorithms.

II. REMAINING USEFUL LIFE OF AMAGB

A. AMAGB gearbox failure analysis

AMAGB is a single input and multi output gearbox mounted on fighter aircraft. The schematic diagram of AMAGB assembly is given in Fig. 1.

Fig. 1. Schematic diagram of AMAGB assembly

To predict the RUL of gear box, it becomes important to study various failure modes and its effect on the life of gear box. Based on Failure Mode and Effect Analysis (FMEA) 2 study, Risk Priority Number (RPN) is computed for all the components of gearbox. The critical components identified are Dynamic carbon seals, Bearing assembly, Casing, Filter, Lubricant, Shaft and Gear. The identified different causes for failure of components are represented in Fig. 2. Most of the failures are caused by contamination of lubricant and inadequate lubrication. The other major factor that affect life of components is poor installation. Excessive load, heating of gear box, handling error & deposits on bearing also leads to damage of components. The other causes for failure are high starting load, no rotation condition, vibration, fluctuating loads, skewed rollers, faults, aeration, rapid pressure change and malfunction or failure of parts.

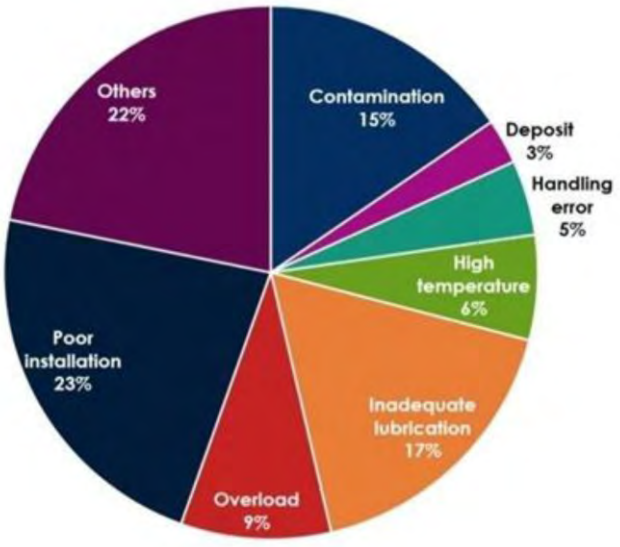


Fig. 2. Causes for failure of gear box

B. Findings of FMEA study

1. The primary failure mode of gear is abrasion. The root cause of failure is inadequate lubrication and contaminants present in the lubricant.
2. The primary failure mode of shaft is fracture caused by bending load and torsional load. The root cause of failure is excessive load.
3. The primary failure mode of spline is cracking. The root cause of failure is centrifugal stress exceeding the permissible stress.
4. The different failure modes of bearing assembly are fatigue failure, wear and lubrication failure. They are caused by contaminant in lubricant and deposit present in bearing.

5. The primary failure mode of dynamic carbon seals is scarring caused by foreign material present in the lubricant and poor installation. Coking of dynamic carbon seals is caused by chemical breakdown or oxidation of hydrocarbon at high temperature.
6. Gear pump assembly: Seizing caused by low volume intake and bridging of the clearance due to thermal expansion; shaft fracture and leakage is caused by blockage of filter which increases the pressure inside the gear pump.
7. The failure modes of casing are blockage in core passage, oil leakage at valves and oil leakage at casing interface caused by contaminant in lubricant, poor fitting of component and vibration respectively.
8. The primary failure mode of lubricant is contamination caused by moisture, wear particles and dirt. Lubricant also fails due to excessive temperature caused by ineffective cooling.
9. The primary failure mode of filter is partial or complete clogging caused by excessive contaminant in lubricant.
10. Mount fails due to excessive vibration caused by loosening of stud due to improper installation.

C. Concept of RUL

The performance of machine over time indicates the state of components which in turn is used to estimate the RUL of components. The plot describing the change in performance of machine over time (condition indicator) is given in Fig. 3. The performance of a machine remains stable under healthy operating condition. This performance deteriorates over time that will result in the failure of components. It is critical to estimate RUL of components to predict faults thereby preventing unexpected failures. RUL is the amount of time a component operates in normal condition at a given instant before fault occurs. When A is the current condition of the component and B is the minimal acceptable condition of the components, then RUL is computed as the difference between the two points. RUL can be represented in number of hours, cycles, days or any other quantity.

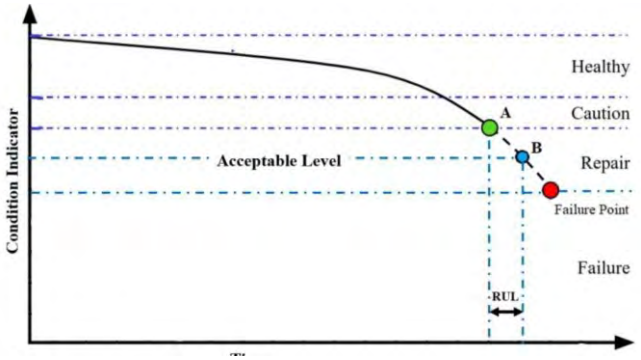


Fig. 3. Concept of RUL

RUL is the useful working time available at any instant before a gearbox fails. RUL is calculated based on the real time data or simulated data collected from gear box and digital twin model respectively. The steps involved in the prediction of RUL of gear box is schematically represented in Fig. 4. [2,3]

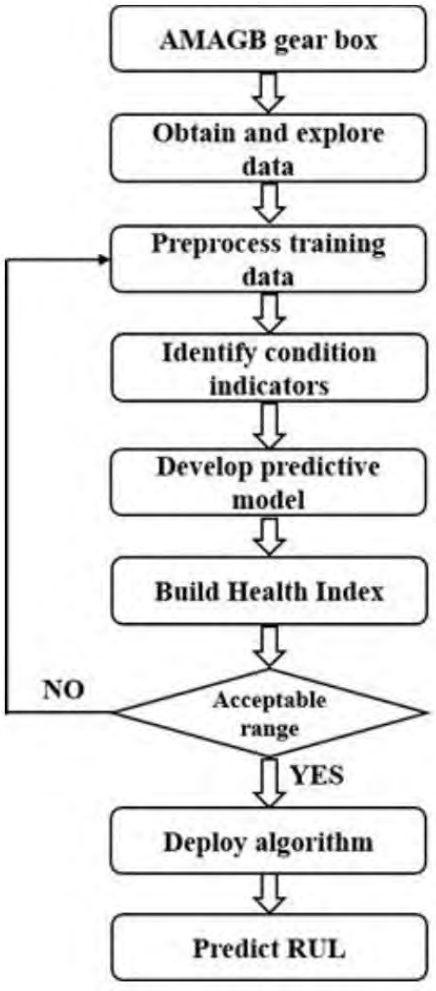


Fig. 4. Workflow for prediction of RUL

D. Concept of Digital Twin

Digital twin is composed of three major components: (a) physical entity in real space, (b) virtual entity in software form and (c) data flow between the two (Fig. 5). [4,5]

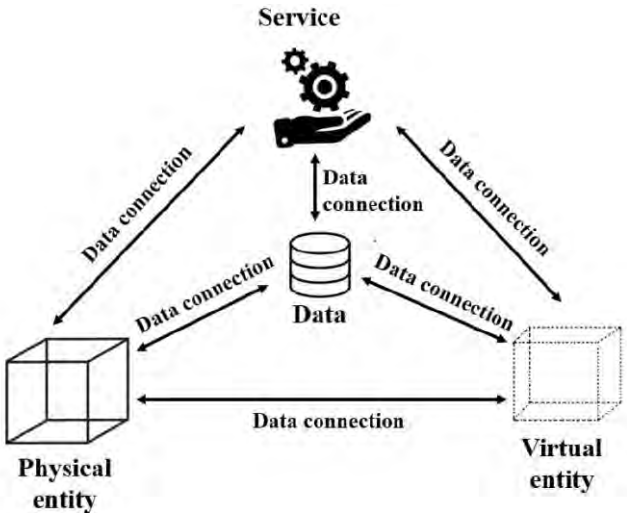


Fig. 5. Digital Twin Architecture

1. Real-time data is collected from the physical entity through sensors and stored in a centralized database unit.
2. Data is processed to be fed to digital twin.
3. Digital twin is built using physical model, dynamics model and simulation model. High fidelity digital twin model is built by integrating real time data with virtual model. At this step, AI algorithms can be applied to verify product design, monitor condition and prevent breakdowns.
4. Establishing a two-way information flow between the physical entity and the virtual entity.
5. Optimization of the digital twin model based on real time data and simulation results.
6. Change of operating condition of physical entity based on simulations results of virtual entity.
7. The service include service for physical entity and virtual entity like monitoring service, diagnostic service, predictive service and control service.

E. Methods to estimate RUL

Survival Model: This method uses proportional hazard model and probability distribution plot to estimate the RUL. This method is applied for cases where failure time data of components and associated covariates are known. Covariates are information related to manufacturing or operating condition. The survival function plot to estimate RUL is given in Fig. 6 (a). [6]

Similarity Model: This method uses database of run-to failure data. RUL is estimated from the run to failure data which closely matches the new data. Estimation of RUL based on similarity model is given in Fig. 6 (b). [7]

Degradation Model: This model is applied to systems whose condition indicator has a threshold value. RUL is estimated by calculating the time taken by the condition indicator to cross the preset threshold value. Estimation of RUL based on degradation model is given in Fig. 6 ©. [8]

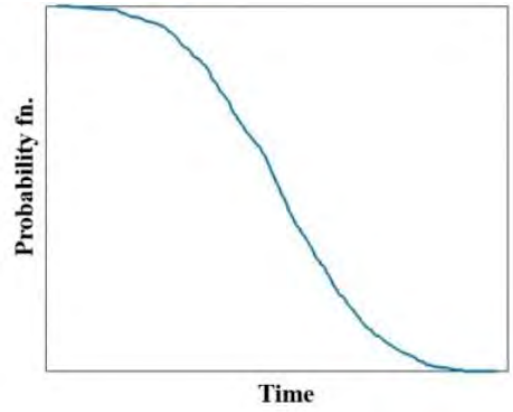


Fig 6 (a). Survival model

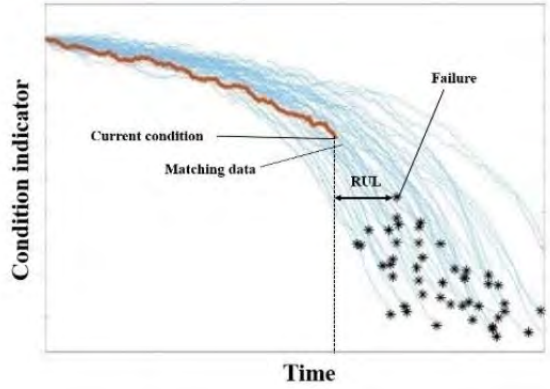


Fig 6 (b) Similarity model

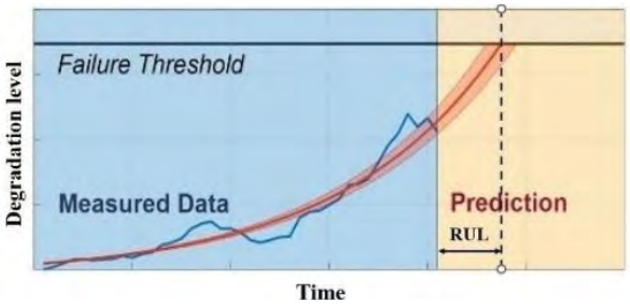


Fig. 6 (c) Degradation model

The process involved in using RUL estimation model is as follows:

1. Select the best type of RUL estimation model based on the available sensor data and historical data. Establish the model for processing data.
2. Train the model to get the accurate prediction result.
3. Estimate the RUL of the component by feeding test data to the trained RUL model.

The RUL estimator models are illustrated in the Figure 7.[9]

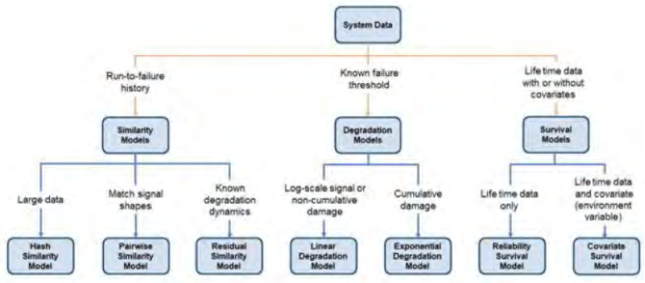


Fig. 7. RUL estimator model

III. DIGITAL TWIN MODEL OF AMAGB

A. Digital Twin model for AMAGB gearbox

The digital twin framework proposed for AMAGB gear box is represented in Fig. 8. The five dimensional elements of proposed digital twin model (MDT) can be represented as follows [10],

MDT = (PE, VE, DD, SS, CN)

PE is the physical entity that consists of real entity, sensors and data acquisition devices.

VE is the virtual entity that consist of physical model, geometric model, behaviour model and rule model.

DD is the digital twin data (PE data, VE data, SS data, knowledge domain data and fused data). SS is the services for PE and VE.

CN is the connection among PE, VE, SS and DD.

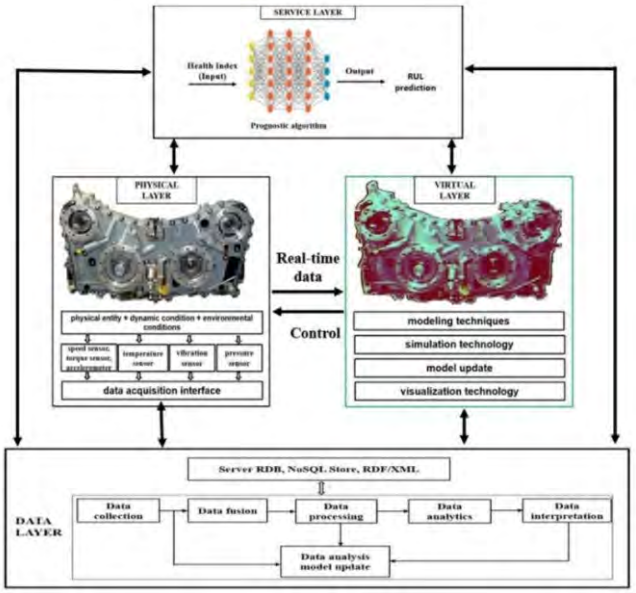


Fig. 8. Digital twin model for AMAGB gearbox

B. Workflow to predict RUL of gearbox

The workflow adopted to predict RUL of the gear box is shown in Fig. 9. Data is collected on real-time basis through sensors mounted on gear test bench. In the pre-processing stage, noise present in the data is removed by application of filters like Kalman filter. The pre- processed signal is decomposed into sub-bands. These signals are then processed to extract time or frequency or time-frequency domain features. Reduced order modelling is employed to improve the computational complexity of model by reducing the dimensionality of data. The selected features based on their influence in degradation process are weight optimized and fed to the degradation model for computation of health index. When the health index value lies in permissible range, RUL value of gearbox is predicted deploying prognostic algorithms such as machine learning and deep learning algorithms.

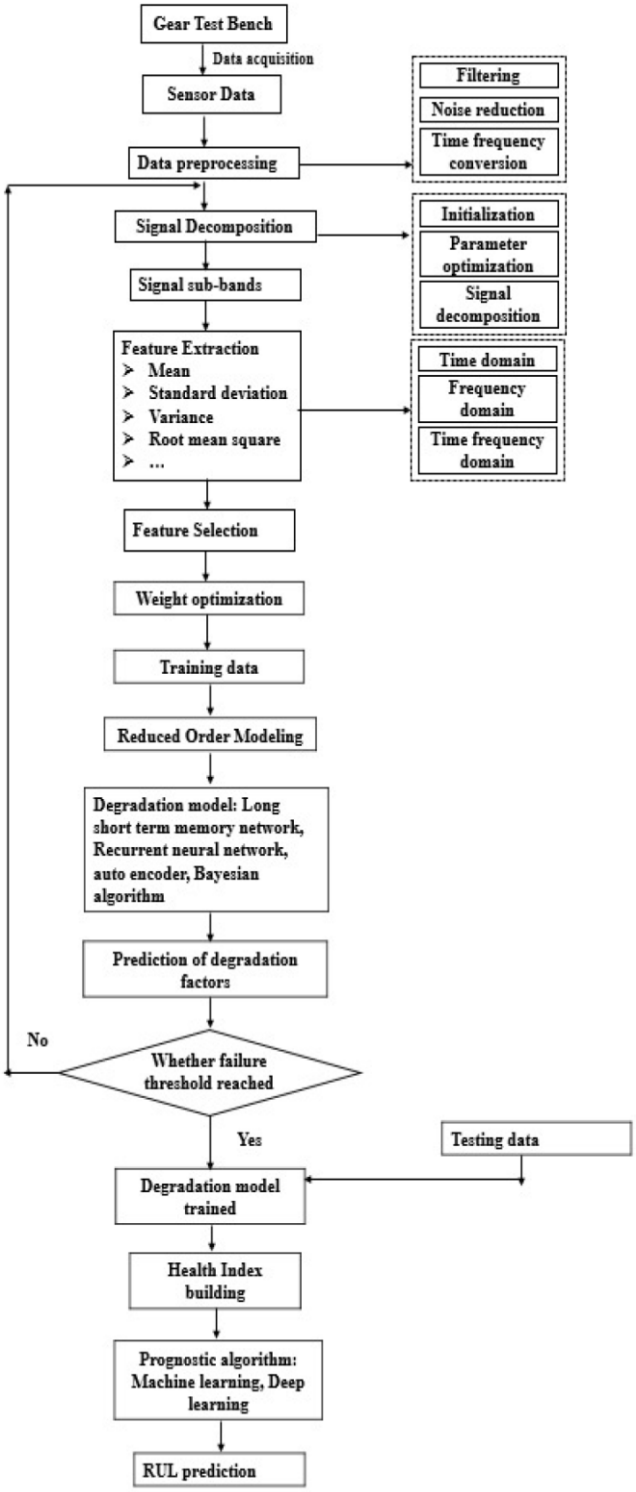


Fig. 9. Workflow to predict RUL from sensor data

C. Fault sensing techniques

i. Vibration analysis
- Dedicated condition monitoring system with sensor bandwidth up to more than 10 kHz.
- Vibration analysis helps to identify improper installation of components, misalignment of shafts or gears and damage in gears or bearing.

ii. Oil sample analysis
- Oil samples are extracted at specific time intervals to check for changes in physical and chemical properties of oil: viscosity, wear debris, color change, ferro-magnetic particle analysis.
- Debris element analysis is useful to trace the faulty components: bearing assembly, gears, casing and so on.

iii. Filter element analysis
- Filter element analysis of used filter cartridges is done to assess the nature of wear debris and material composition.
- Identified material composition indicates the failed components: bearing assembly, gears, casing and so on.

iv. Strain gauge load sensor
- Load sensors mounted on the shaft to measure the load. This help to prevent the fracture caused by high starting load.

v. Temperature sensor
- Any change in the temperature of the system is detected by temperature sensor. Most commonly used temperature sensors are resistance thermometer and infra-red camera.

vi. Acoustic sensor
- Acoustic sensor measure the sound waves caused by the components and converts them into electrical signal.
- This helps in detecting failures like cracks, wear, abrasion and de-bonding of surface that happens in gear, shaft, bearing assembly and so on.

vii. Pressure sensor
- Oil pressure is a good indicator of proper oil flow. Any change in the pressure of oil indicates the blockage in filter.

D. Signal processing and fault classification

i. Data acquisition

Data can be measured data, simulated data or historical data. The collected data covers range of operating condition from healthy condition to unhealthy condition. Data from the physical equipment can be collected either continuously or at specific intervals of time. Data pertaining to typical faulty condition can be generated through simulation of digital twin model. This approach enables generation of sensor data with all possible fault combinations and faults of varying severity.

ii. Preprocessing data

The raw signal contains noise which must be cleaned before being fed to algorithm for extracting condition indicators. The different techniques that are employed to preprocess data are listed below in Table 1. [11]

TABLE 1. Techniques for data preprocessing

Basic pre-processing	• Fill or remove gaps in data • Shifting mean • Remove noise and unwanted data • Maintain same time scale across the range of data
Filtering	• Confine data in a pre-defined frequency range • Decompose a signal into two or more sub-bands
Time domain pre-processing	• Plot the signal as a function of time • This gives information about the change of signal properties with respect to time • The time domain features are mean, standard deviation, root mean square, peak, skewness, kurtosis, crest factor, clearance factor, shape factor and impulse factor
Frequency domain pre-processing	• The input signal is converted into two or more bands of different frequencies • This gives insight into the frequency content of the signal and contribution by specific frequency to the overall signal • The frequency domain features are mean frequency, frequency centre, root mean square frequency, standard deviation frequency, spectrum peak ratio
Time-frequency pre-processing	• Represent the signal in both time and frequency domain • This method is used to extract critical information that may not be apparent in time and frequency domain alone • The time-frequency domain features are mean, standard deviation, skewness and kurtosis.

iii. Feature selection

Feature selection is an important step in estimation of RUL. Feature selection reduces the size of data by selecting a specific set from whole data and by calculation of standard parameter values from the selected data. Feature selection metrics ranks the effectiveness of condition indicator in predicting degradation process on scale ranging from 0 to 1. Three ways of ranking condition indicators are listed below.

Monotonicity: After continuous operation of the system, a typical condition indicator has a monotonic positive or negative trend. This change in the trend of condition indicator gives the extent of damage.

Prognosability: This method measures the variability of feature at failure relative to the range between its initial and final values. A more prognosable feature has less variation at failure relative to the range between its initial and final values.

Trendability: This methods compares the similarity between the trajectories of a feature measured in multiple run-to-failure experiments. Trend ability of a candidate condition indicator is defined as the smallest absolute correlation between measurements.

iv. Condition indicator and fault classification

Condition indicator is a feature extracted from the machine data that indicates the operating status of the system. Condition indicator is useful to detect the fault and for the estimation of RUL. After computation of fault data, the results are plotted on a confusion matrix (Fig. 10) [12]. On the confu-

sion plot, the numbers 1 to 7 represent the fault codes. The rows and columns correspond to the predicted values and true values respectively. The diagonal numbers indicate number of times a typical fault is classified correctly. The off-diagonal number indicate number of times a typical fault is classified incorrectly. The accuracy of classification of a typical class of fault is given at the end of class. The overall prediction accuracy of the model is calculated taking the mean of prediction accuracy of all fault codes. The prediction accuracy of the algorithm is given in bottom right cell of confusion plot.

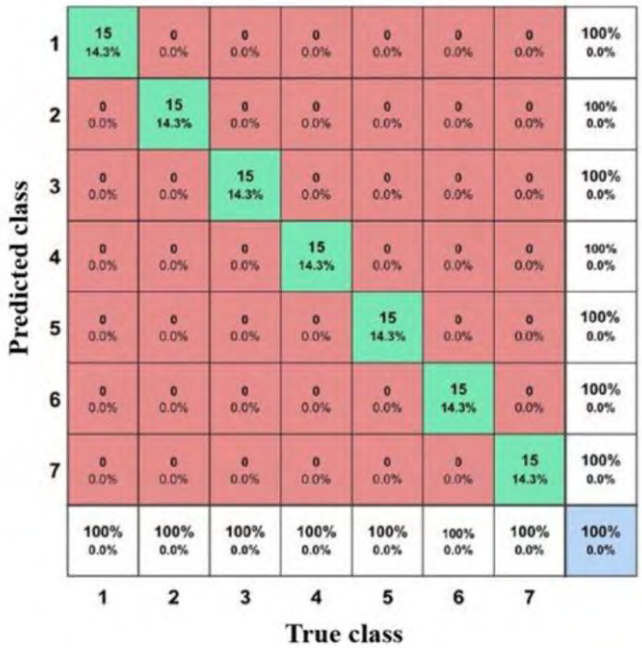


Fig. 10. Confusion plot

IV. CASE STUDY

The schematic diagram of gear test unit built using Matlab Simulink is given in Figure 11. Monitoring sensors such as flow meters, pressure sensors, and temperature sensors can be additionally installed in the test system to monitor the operating state of the system. Due to complexity of the gearbox, a simple gear system with driving gear and driven gear which is similar in operation to the aircraft gearbox is built to further study the acceleration of the gear system. Simulink model is developed for simple gear consisting of driving gear and driven gear. The solid model of gear system is built using SolidWorks (Fig. 12) and imported to the Simulink model. The driving and driven gears are constructed with 63 and 44 number of teeth. The gears are equipped with acceleration sensor to measure the acceleration of driving and driven gear in m/s2. An input torque of 20N-m is given to the driving gear from a torque source. After a simulation time of 10s, the plot of acceleration with respect to time extracted is shown in Fig. 13. Fault in the gears are inducted by cutting the teeth of gears. The output acceleration for 10s is extracted for the faulty gears in the similar way as before (Fig. 14). A huge difference in the output of gears in normal operating condition and faulty condition is observed. Likewise data can be generated for different operating condition of the gearbox which is further used for the estimation of RUL of gearbox.

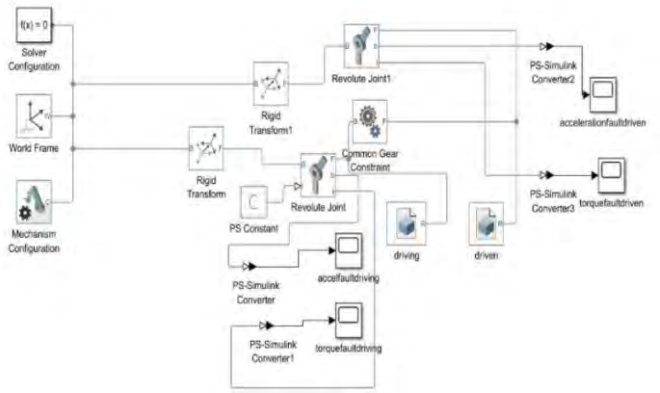


Fig. 11. Matlab Simuink Model

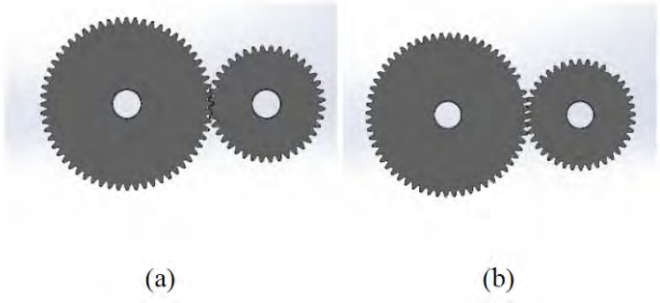
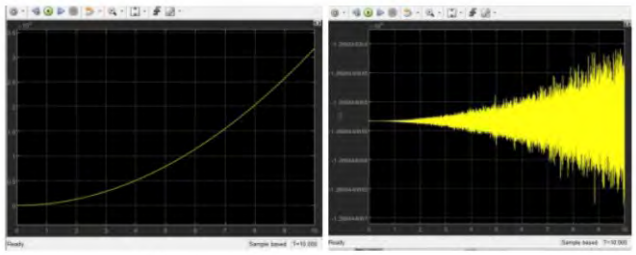


Fig. 12. Gear configuration (a) normal operating condition (b) Induced broken teeth



(a) (b)

Fig. 14. Plot of acceleration under faulty condition (a) Driving gear (b) Driven gear

V. CONCLUSION

In this paper, RUL estimation of AMAGB gearbox based on digital twin concept is discussed and workflow to predict RUL from the collected data is presented. The outcome of the study are given below.

- The salient features of AMAGB gearbox and its significance of usage in fighter aircraft is discussed. The critical components of high risk value are identified based on computed RPN value. Contamination and inadequate lubrication are the primary cause affecting the life of components. Poor installation of components also has influence on the life of gearbox. The other factors identified are high starting load, no rotation condition, vibration, fluctuating loads, skewed rollers, faults, aeration, rapid pressure change and malfunction of parts.
- Five dimensional digital twin model for real-time monitoring of the gearbox has been proposed. RUL is estimated from the data collected from the physical entity and the simulation data from the digital twin model. The proposed digital twin model provides a reliable solution for real time monitoring, fault diagnosis and assessing the RUL of gear box.
- Implementing digital twin technology helps in better management of system by preventing unexpected failure of the system. This will enable to achieve better efficiency of the system.
- A case study is done by testing a simple gear system in Simulink Matlab model for 10s. The simulation is run for 10s under both normal operating condition and faulty condition. Significant differences in the output acceleration for different simulation conditions are observed.

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Virtual Fatigue Testing of a fighter aircraft using a Fatigue Digital Twin: A framework and challenges

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Abstract - The durability demonstration of major airframe structures, and aircraft Full Scale Fatigue Testing is a key milestone in the development, qualification and certification of any new fighter aircraft. Fatigue tests are conducted to identify any unforeseen fatigue related issues that could compromise the structural integrity and limits the life span of an aircraft. However, the conduct of these tests demands enormous amount of resources in terms of time, cost and efforts. With the emergence of advanced simulations and continuous improvement in computational capabilities, an opportunity exists to reduce the number of necessary physical structural fatigue tests by replacing them with Virtual Fatigue Tests. This paper discusses the framework and challenges towards the development of a Fatigue Digital Twin and the viability of the Virtual Fatigue Testing of a fighter aircraft as a replacement of physical fatigue testing.

Keywords - Digital Twin, Fatigue Digital Twin, Full Scale Fatigue Testing, Virtual Fatigue Testing.

I. INTRODUCTION

Prevention of pre-mature failure due to fatigue in structural parts of an aircraft has been a key challenge in aerospace design engineering since decades. The technological advancements continually brought in improvements in design concepts, better materials, advanced fabrication processes, and more realistic information about in-service requirements [1]. In-spite of such advancements, demonstration of structural durability of an aircraft by conduct of Full Scale Fatigue Tests (FSFTs) has proved to be the most reliable means for verification and validation of the design, production and durability of the aircraft. Thus, FSTFs are still one of the mandatory certification requirements enforced by regulating agencies for any new type of fighter aircraft [2]. The time, cost and efforts associated with the conduct of FSTFs are enormous and often prohibitive in development and qualification of any new military aircraft. In the recent times, new approaches such as 'Qualification By Analysis' and 'Virtual Testing' along with continuous improvements in high performance digital computing have attracted the interest of researchers towards transformational concepts such as Digital Twins/Digital Thread and even the concept of Virtual Fatigue Testing to demonstrate the durability of an aircraft [3].

The idea of the Digital Twin was propounded by NASA and U.S. Air Force, aimed at a paradigm shift of physical testing to virtual testing for certification, fleet management and sustainment [4]. A Digital Twin is an accurate virtual representation of an individual physical asset which mirrors its life.

The term Virtual Fatigue Testing (VFT) has emerged in the literature two decades ago [5], since then the virtual fatigue testing of airframe structures is an alluring approach towards the development, qualification and certification of an aircraft. In order to equip a digital twin of an aircraft for virtual fatigue testing, the digital twin must inherent the capability of mimicking fatigue behaviour at different physical scales along with simulating stochastic behaviour of fatigue. Such specialized virtual representations are referred as Fatigue Digital Twin (FDiTw) [6]. Fatigue Digital

Twin is an essentially equipped virtual model capable of capturing structural fatigue behaviour at different physical scales which includes, damage accumulation, fatigue crack nucleation and crack growth, as well as the probabilistic nature of fatigue.

The concept of Fatigue Digital Twin for Virtual Fatigue Test is still at a nascent stage of development. Recently several research efforts are dedicated towards exploring feasibility and challenges [7]; collaborative efforts [3]; and hybrid approach [2] towards Virtual Fatigue Tests. However, a comprehensive framework of Fatigue Digital Twin for Virtual Fatigue Testing is still lacking in the literature. Hence, there is a need to define a sequential approach to develop a Fatigue Digital Twin for VFT.

In this study, a conceptual framework towards development of Fatigue Digital Twin for Virtual Fatigue Testing has been proposed and associated challenges in achieving that framework are highlighted.

II. VIRTUAL FATIGUE TESTING

Digital twin is an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that mirrors the life of its corresponding physical asset [4]. Digital Twin which is capable of mirroring fatigue response i.e. Fatigue Digital Twin, is a prerequisite for Virtual Fatigue Testing. Fatigue Digital Twin is essentially specialized in mimicking fatigue behaviour at different physical scales, along with simulating stochastic behaviour of fatigue. Virtual Fatigue Tests could be defined as an ultra-high-fidelity simulation of highly precise Fatigue Digital Twin of a physical test asset, to mirror the fatigue response at different physical scales. Comprehensive modelling of integrated multidisciplinary physics based models, multiscale damage models and uncertainty quantification are necessary for capturing fatigue behaviour and effective implementation of Virtual Fatigue Testing.

A. Conceptual Framework

The framework of Virtual Fatigue Testing encompasses development of an ultra-high fidelity Fatigue Digital Twin model, which is an organized collection of as-built configurations, augmented with multiscale, multidisciplinary physics based models to capture fatigue behaviour. A sequential approach towards development of a fatigue digital twin from a generic baseline digital model is outlined, which forms the basis of overall framework of Virtual Fatigue Testing using Fatigue Digital Twin.

A baseline Digital Model (DiMo) is a generic representative model of an aircraft or a component (thereafter referred as 'asset'), without capturing any specificity in terms of geometric features, material properties and structural behaviour of an individual asset. In other words, baseline digital model is not a unique digital replica of an individual asset.

In order to precisely capture the exclusive features of an asset, an 'as-built calibration' of a baseline digital model is necessary. An as-built calibration is referred as a process of precisely incorporating geometric features, material microstructure characteristics, defects, flaws, fabrication anomalies and assembly irregularities at different physical scales, representing highly accurate attributes of a particular individual asset. Hence, a precisely calibrated model of an as-built configuration, capable of mimicking comprehensive design characteristics, material microstructure behaviour, defects, flaws, fabrication and assembly deviations etc. is a structural Digital Twin (DiTw) of a particular individual asset as illustrated in Fig. 1.

The main design parameters which affect the fatigue response of an asset are material, geometry, loading and environment. As-built calibration of Digital Twin embeds specificities in terms of material and geometry of a particular individual asset. However, to impart fatigue capabilities using various physics-based fatigue models, fatigue calibration of the digital twin is indispensable. The different physics-based fatigue models need to be necessarily coupled with each other, in order to capture interactions among material state, structural responses, loading histories and environmental conditions. Hence, the fatigue

calibration of a Digital Twin (DiTw) encompasses incorporation of damage models, capable of capturing damage behavior in terms of crack nucleation, crack growth, damage tolerance, residual strength and probabilistic nature of fatigue. A fatigue calibrated Digital Twin, capable of mimicking fatigue behavior is referred as Fatigue Digital Twin (FDiTw). Fatigue calibration schematic of a digital twin is illustrated in Fig. 2.

Virtual Fatigue Testing is a high accuracy simulation of Fatigue Digital Twin model, mirroring its testing environment comprising of complex loading spectrums, boundary constraints, and environmental conditions. During Virtual Fatigue Testing of Fatigue Digital Twin, it is necessary that the damaged material state during complex repetitive loading and the damage models as calibrated in the Fatigue Digital Twin must interact with each other so that the possible synergistic effects are captured in the fatigue response [7]. The interactions between the damaged material state and fatigue damage models during Virtual fatigue Testing of a Fatigue Digital Twin is illustrated in Fig. 3.

To achieve the ultimate objective of fully predictive virtual testing, it is necessary that the Digital Twin, fatigue models and virtual testing, all three should be in conjunction with each other. The structural and fatigue response of Fatigue Digital Twin needs to be coupled with each other during Virtual Fatigue Testing. Digital Twin and fatigue models must communicate bi-directionally with Virtual Testing. Interactions between different constituents of the framework such as digital twin, fatigue models, virtual testing, structural and fatigue responses need to be two-way couplings, in order to precisely simulate an as-built configuration, capture fatigue behavior and mimic testing environment. Integrating as-built calibration, fatigue calibration and bi-directional couplings of virtual fatigue testing with fatigue digital twin and structural/fatigue response, a conceptual framework for the Virtual Fatigue Testing is illustrated in Figure 4.

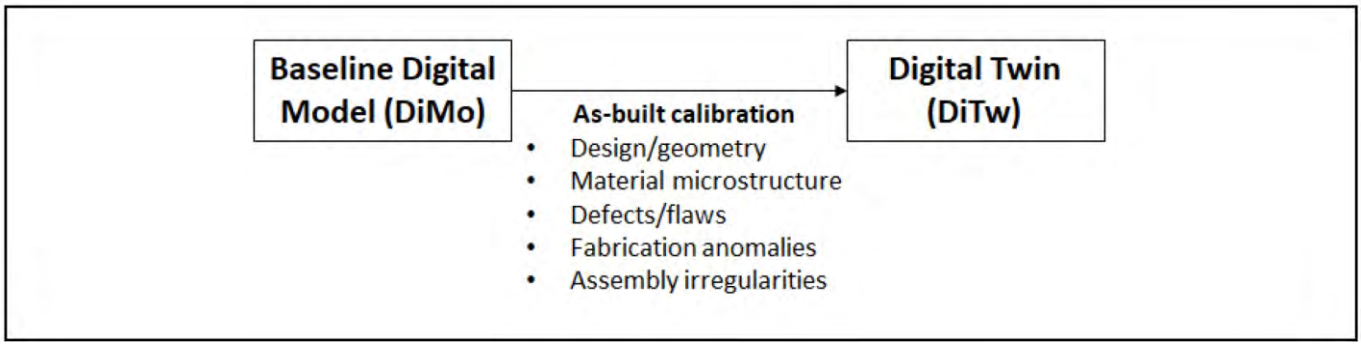

Fig. 1. Schematic of As-built calibration of a baseline Digital Model to Digital Twin.

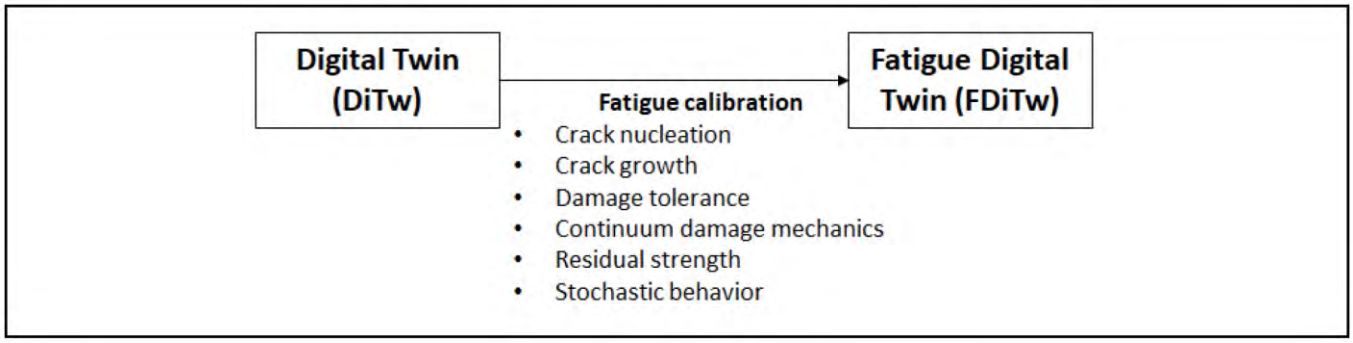

Fig. 2. Schematic of Fatigue calibration of Digital Twin to Fatigue Digital Twin.

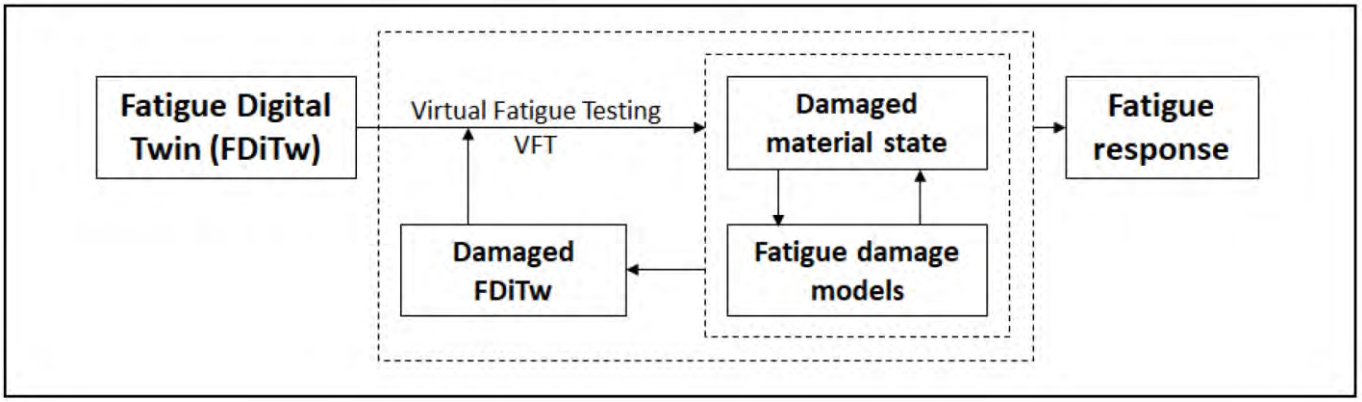

Fig. 3. Schematic of material state interaction with damage models during virtual fatigue testing.

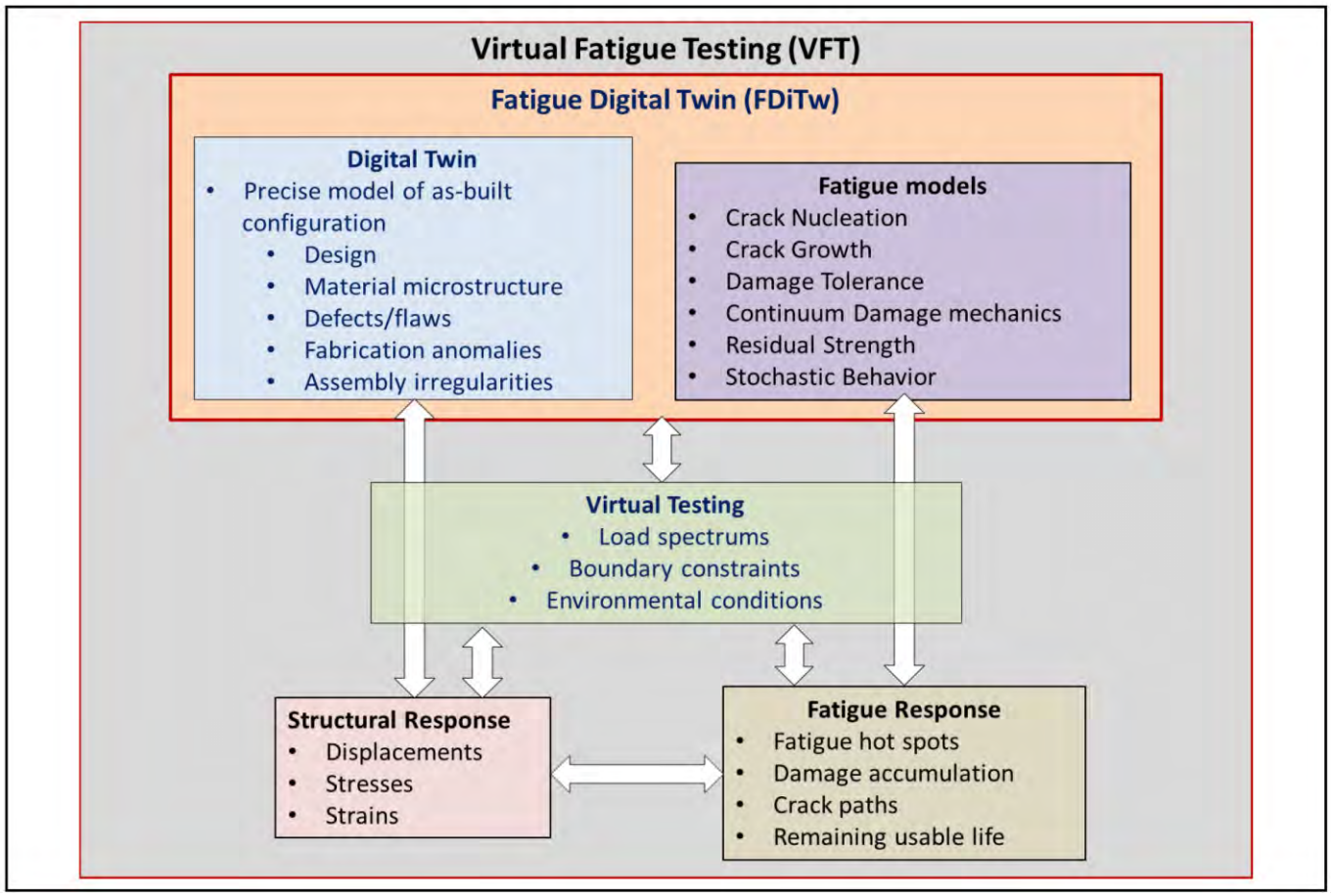

Fig. 4. Conceptual framework for Virtual Fatigue Testing (VFT) using Fatigue Digital Twin (FDiTw).

B. Challenges

The idea of Digital Twin itself is a grand scientific and technological challenge [8]. Recently, researchers also noted that, incorporating structural fatigue in Digital Twin technology at airframe level is too complex, too large and demands collaborative efforts towards progressive developments in aircraft fatigue modelling and experimentation [3]. The extreme requirements of Digital Twin necessitates revolutionary technological advancements in the areas of multidisciplinary physics modelling; multiscale damage modelling; integration of structural, material and damage models and uncertainty quantification [7]. A major challenge associated with full predictive virtual testing technology is attributed to the novelty of the concept and inherits plethora of evident and hidden challenges. Some of the immediate

challenges that can be foreseen are:

a) Comprehensive and fundamental understanding of multidisciplinary physics based physical processes.
b) Characterization of material properties at different physical scales.
c) Arbitrariness of fatigue response due to stochastic nature.
d) Computational requirements for ultra-high-fidelity simulations of full-scale models with acceptable computational costs.
e) Realistic and representative loading spectra.
f) Acceptability, credibility and reliability of virtual tests.

Looking at the requirements of Virtual Fatigue Testing (VFT) technology, it is evident that the challenges are multi-fold, ranging from understating of integrated multidisciplinary physics, multi-scale physical modelling, uncertainty quantification to cost effective high performance computations. These challenges need to be pursued collaboratively and progressively in order to achieve highly ambitious goal of fully predictive virtual testing technology.

III. CONCLUSION

Fatigue testing is a fundamental step in the airworthiness certification for any new fighter aircraft. Time and costs associated with these tests motivated researchers to look towards more efficient and cost-effective approaches. Virtual Fatigue Testing using Fatigue Digital Twin is a promising way-forward towards realization of fully predictive virtual testing technology. Virtual Fatigue Tests are ultra-high-fidelity simulations of highly precise Fatigue Digital Twin of a physical test article. A conceptual framework has been presented, encompassing a Digital Twin, augmented with fatigue models to capture fatigue behaviour of a structure and mirroring the testing environment for Full Scale Fatigue Testing. It is noted that the realization of fully predictive virtual testing technology poses enormous challenges in terms of multidisciplinary physics understanding, mimicking test environment and computational requirements. However, the ever-increasing high performance computational capabilities and improving accuracy of simulations, encourages research efforts towards adoption of new revolutionary approach of virtual testing technology.

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Duty cycle based digital twin approach to calculate remaining useful life of an aircraft gearbox.

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Abstract - For any gearbox fitted in the aircraft no aspect of performance is more important than reliability. Remaining useful life calculation after every flight operation for aircraft gearbox is always a challenge for aero industry. The standard based life calculation is widely used across all industries where the load cases acting on gearbox are derived by condensation technique. The stress due to these load cases is compared against the SN curve of rotating components such as gears and bearings and life estimation is done. The condensation technique is called as duty cycle condensation, where loads acting on aircraft gearbox are collected at certain very small-time interval and these loads which are billion in numbers are reduced to handful of load cases. This is done by collecting the data from an instrumented aircraft. Although the technique is most reliable to account how accurate a designer has considered the loading conditions, it is still not sufficient to establish the reliability of gearbox as every gearbox in flying aircraft in particular military aircraft experiences different loading conditions. This is due to the fact that condensed duty cycle is generated for an instrumented test aircraft with an assumption that every flying aircraft has a same loading pattern, operating conditions, same micro geometry of gears, same micro level assembly parameters and tolerance stack up etc. The micro level parameters such as manufacturing and assembly tolerances along with real life flying conditions can lead to difference in remaining useful life of every aircraft gearbox. The technique proposed here is a digital twin-based approach where a real-life data is communicated to a cloud platform and then fed to Romax which is the tool used to condense the flight data and establish the reliability by calculating the remaining useful life of gears and bearing in a holistic approach. The method proposed in this paper is developed by Hexagon and implemented for a globally renowned automotive OEM where it evaluates the reliability of all the gearboxes which are in the field and removes the gap between 'predicted reliability and 'observed reliability'. The term 'Digital Twin' has been around us in recent years and spoken widely but rarely implemented in its true sense. The paper will argue that the Digital Twin is computerized version of physical asset where physical prototype and simulation model accompany one another as the physical asset carries out its operation in-service, with the Digital Twin providing information on the performance (or predicted performance) of the physical asset. This paper paves a way to enormous potential available with Aero industry to develop far superior predictions of gearbox reliability as we move to a situation where telematic data is becoming more readily available.

I. Defining the Digital Twin

The term digital twin has been much talked in recent past and has various forms with respect to its purposes. In 2001 Michael Grieves [4] defined digital twin as 'conceptual idea for PLM' where 'Twin' is the digital information embedded in physical asset itself and be linked with physical asset throughout its lifecycle. From then idea of 'conceptual idea pf PLM' he expanded this till 'Digital Twin Environment' in 2016. In the expansion of Digital Twin idea, he discussed Digital Twin Prototype DTP for design phase, Digital Twin Instance DTI where the 'Twin' is linked to physical prototype throughout its lifecycle and from there it is interesting to see that he talks about the aggregate of DTIs, and he termed it as 'Digital Twin Environment'. In summary the digital twin is a

digital representation of physical asset under inspection for various reasons. There can be a digital twin of the design model, prototype under testing, under series manufacturing or product under intended service. In all the cases digital twin is expected to mimic the operating condition and let the user know its reliability. Along with reliability, remaining useful life of gears and bearings is also a concern for aircraft gearboxes under use. Barry James and Lou Long [7] from Hexagon AB presented the idea of digital twin for a transmission reliability based on field data of an automotive running in US. The duo summarized that the reliability of bearings in a gearbox is greatly affected by field conditions. Many of the reliability papers published so far use the Weibull distribution and uses the Weibull shape parameter (Dr. Hein et al [8]) which is different in different papers. The digital twin proposed here is same as proposed by Barry James and Lou Long [7] with an addition of duty cycle condensation to accommodate the gap of converting the field data into meaningful duty cycle. For the purpose of this paper the digital twin is the digital representation of physical prototype with function of reading the field condition and analyzing them to establish the reliability of gearbox and its remaining useful life with the probability of survival.

The aim of the paper is to evaluate the remaining useful life of an aircraft gearbox as it's safe functioning is foremost important than its performance. The likelihood of failure increases as the gearbox ages and hence it is important to evaluate as how much life is remaining in the gears and bearing after every flight sortie. The life consumed and the operating loads it has gone through will calculate the reliability of the gearbox. The digital twin proposed here will use the operating data which is discussed later in the paper and condenses it with a scientific method called 'damage matching' criteria of gears and bearings. The author has earlier published a paper 'Damage Matching Criterion for Development of Accelerated Duty Cycle from Road Load Data and Achieving Right Duty Cycle to Determine Gear and Bearing Durability' [6] is referred here. The proposed digital twin uses the flight data and condenses it to make a duty cycle and this condensed duty cycle is used to calculate remaining useful life along with reliability.

1.1 Cloud based digital twin.
As discussed earlier the paper uses the same digital twin defined by Barry J et al [7] this consists of a model of a gearbox in Romax Enduro which is a proprietary product by Hexagon AB Ltd and been in use since 1994 by global automotive and aerospace OEMs. The digital twin proposed uses the CAN data uploaded to cloud and reads it in Romax Enduro to condense and calculate the remaining useful life and system reliability.

1.1 Cloud based digital twin.
As discussed earlier the paper uses the same digital twin defined by Barry J et al [7] this consists of a model of a gearbox in Romax Enduro which is a proprietary product by Hexagon AB Ltd and been in use since 1994 by global automotive and aerospace OEMs. The digital twin proposed uses the CAN data uploaded to cloud and reads it in Romax Enduro to condense and calculate the remaining useful life and system reliability.

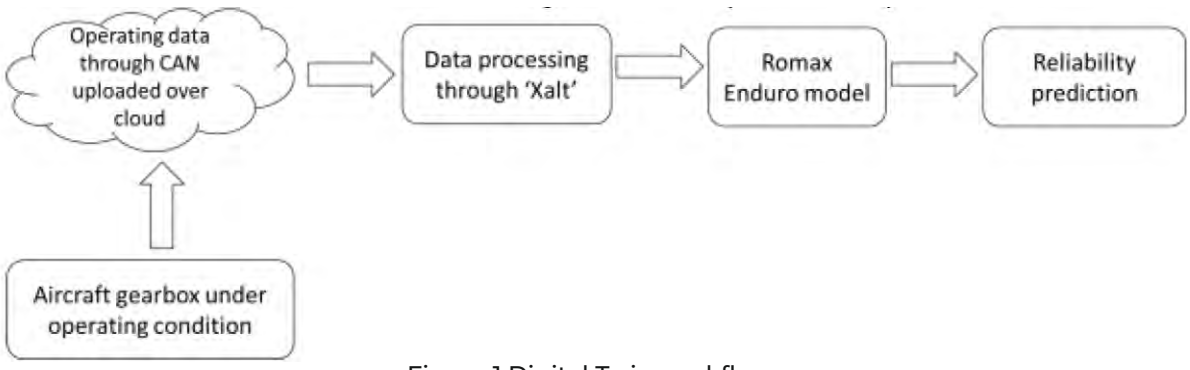

Figure 1 Digital Twin workflow

The key ingredients of aircraft transmission are gears which are rated while designing by using ISO 6336 or similar standards from DIN and AGMA, whereas bearings are rated using ISO 16281. These standards are evolved over many decades and these two standards is the basis of this paper. Both ISO 16281 and ISO 6336 part 1 to 6 output component fatigue damage. This does not predict failure. Rather, 100% damage for the L10 life of bearings indicates 10% failure, whereas 100% damage (a safety factor of 1.0) for gears indicates 1% failure.

Even though the paper talks about gearbox parameter from its main parts, gears and bearing only there is no doubt that the digital twin for complicated systems used in aircraft has a great potential to give the maximum insight in the product flying in the skies. Author assumes that the aircrafts are fitted with CAN instrumentation to transmit the necessary data to cloud and available to read in required format compatible to be read in proposed set up. The data required from CAN at 1Hz frequency is –

- Speed at the gearbox input shaft
- Torque at gearbox input shaft
- Lubricant temperature
- Power drawn at each sink in gearbox.

The last point mentioned is because of the nature of aircraft gearbox as it has multiple outputs at a given time and power has been drawn from these shafts to run various accessories such as oil pump, alternator etc. Depending on how aircraft gearbox is instrumented it is possible to measure it in direct or indirect manner. This data will be imported in Romax Enduro, and condensation is carried out. Author proposes the above-mentioned data transmitted to cloud and then import it, process it in prescribed format so that it is readable. The frequency of the data import can be decided based on the cost, complexity and insight required in the system. Data integration, the ability to pull data across the Cloud and integrate different solutions is also required. In this respect, Hexagon AB collaborate with its own solution 'Xalt' for which Hexagon AB have extensive experience in integrating diverse data systems. Xalt Integration is the tool that links different systems together, and Xalt Mobility presents the results and provides web-based access to the user.

1.2 Defining the operating load conditions

As mentioned earlier author has written a paper [6] on the said subject which shows the method as how the road load data can be converted into meaningful duty cycle for an automotive. Same methodology is proposed here by replacing automotive with some aircraft under studies

1.3 From operating loads to duty cycle

The gearbox in the flight under operating scenario experiences varied conditions of power demand from various accessories. The measured data across these varied conditions at every millisecond will have millions of data points. The conversion of these millions of data points into handful of load cases is required to calculate the life of gears and bearings. This conversion of data points is called condensed duty cycle. This duty cycle is essential as all the time direct fatigue simulation over millions of data pints is not possible. The handling of millions of data points manually is impractical approach. Although condensation technique is used by Romax inventors since last fifteen years for designing the gearbox it is also leveraged to use in predicting reliability of gearbox. Duty cycle condensation technique is useful for test bed conditions as well, where the loading condition is accelerated to shorten the testing time. The digital twin for test bed condition will have to use this technique and accelerate the testing time. The digital twin discussed in this paper is for lifetime twin envisioned by Hexagon as shown in Figure 2

Figure 2 is the digital twins visualized by Hexagon and are across the life cycle of a product under study. The Design Twin is the digital asset of a prototype transmission under test and send the data to design simulation to improve the design against the error between design load cases and prototype test cases. The manufacturing twin is the one which considers the product under series manufacturing and further fine tunes the design against the load cases experienced by transmission under production on a test rig. Where as 'Lifetime Twin' is the one which is discussed in this

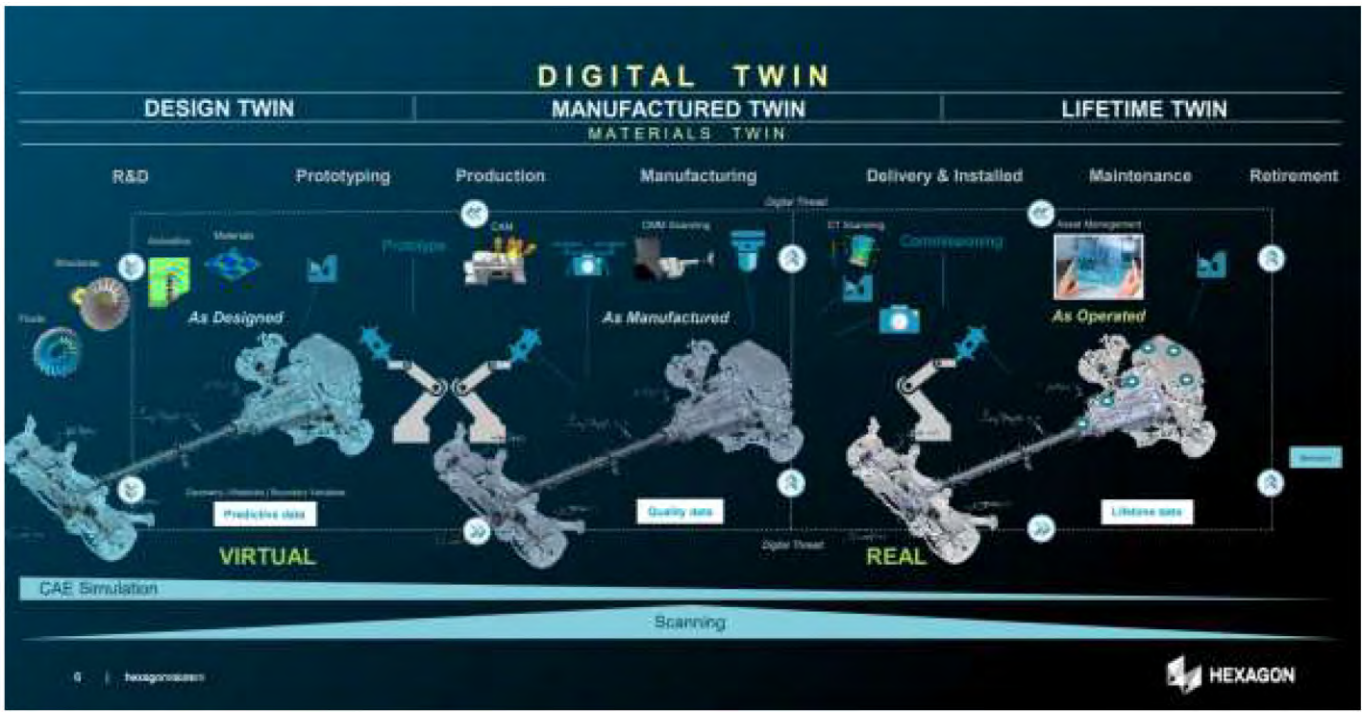

Figure 2 Digital twin for virtual and real-world conditions

paper where twin is mainly used to confirm the reliability of transmission in terms of its remaining useful life.

Duty cycle is a set of load cases with specific time duration to each one which designer apply to the gearbox against which the life expectancy of the gear box is sought. The damage for every entity which is subjected to cyclic load is calculated in terms of life in hours and/or percentage damage. The damage is calculated for each load case and then it summed up to see the total damage and life. A Miner's rule given in Equation 1 is used to calculate the damage of gears and bearings. Miner's rule is a linear damage hypothesis and calculate the total damage. The gear damage is a fatigue phenomenon and Miner's rule is widely used in gear industry to calculate the accumulated damage [9]. In the Equation 1 N1 is actual number of cycles and Nf1 are permissible number of cycles for 1st load case, N2 is for 2nd load case and so on. The damage is added up to the given number of load cases. However, Miner's rule has two limitations, it does not account for the order in which the stresses are applied, and any stresses less than the fatigue limit strength are ignored, i.e., below point D in Figure 6. Later limitation has negligible effect on life calculation as any gear or bearing operating below point D is running at very low load and does not produce the stresses worth considering for damage.

$$\text{Damage} = \frac{N1}{Nf1} + \frac{N2}{Nf2} + \frac{N3}{Nf3} + \cdots .. + \frac{Nn}{Nfn}$$

Equation 1

There are three methods proposed in the paper [6] among which we are using equivalent load method which considers the slope of SN curve of gear and bearing material. The key point considered here is to apply the slope as per the failure criteria and not just one single slope value. The slope value will be different for different materials and failure criterions and varies from module to module as well. As the method is proposed for aircraft Author strongly advocates to measure the SN curve for the gear the range of module and material by means of testing.

The factor of safety is calculated for each gear and bearing using the standard ISO 6336 and DIN ISO 16281 respectively. The sample plot of one single

load for one any one failure criteria is conceptually shown in Figure 6.

In the Figure 6 'r' is the remaining life of entity under study, i.e., gear or bearing. The percentage damage is added as per Equation 1 and even if the safety factor of each operating point is above 1.0 the damage can exceed the 100 % mark when the damage is added for each such load case. As the damage crosses 100 % mark the part is claimed to be failed. The duty cycle condensed from flight operating data will calculate the percentage damage for each gear and bearing and subtract from its permissible life i.e., 100% damage and will give us the value of remaining useful life.

Based on the suggested technique the flight load data can be condensed into smaller number of load cases with damage is being matched for all gears for contact and bending and for all bearings.

A sample summary of calculation is explained below.

The direct fatigue simulation is done using Hexagon's Romax DT software where it considers the SN curve for contact and bending for selected gear, and if we select many gears and that of different material then Romax DT considered SN curve for each gear and bearing with respect to their material.

* The SN curve for contact and bending are different from each other and their slopes are different to each other

It is assumed that same CAN data will be similar to load data used in this example and it looks like as shown in Figure 4

The CAN data is binned, and then equivalent load

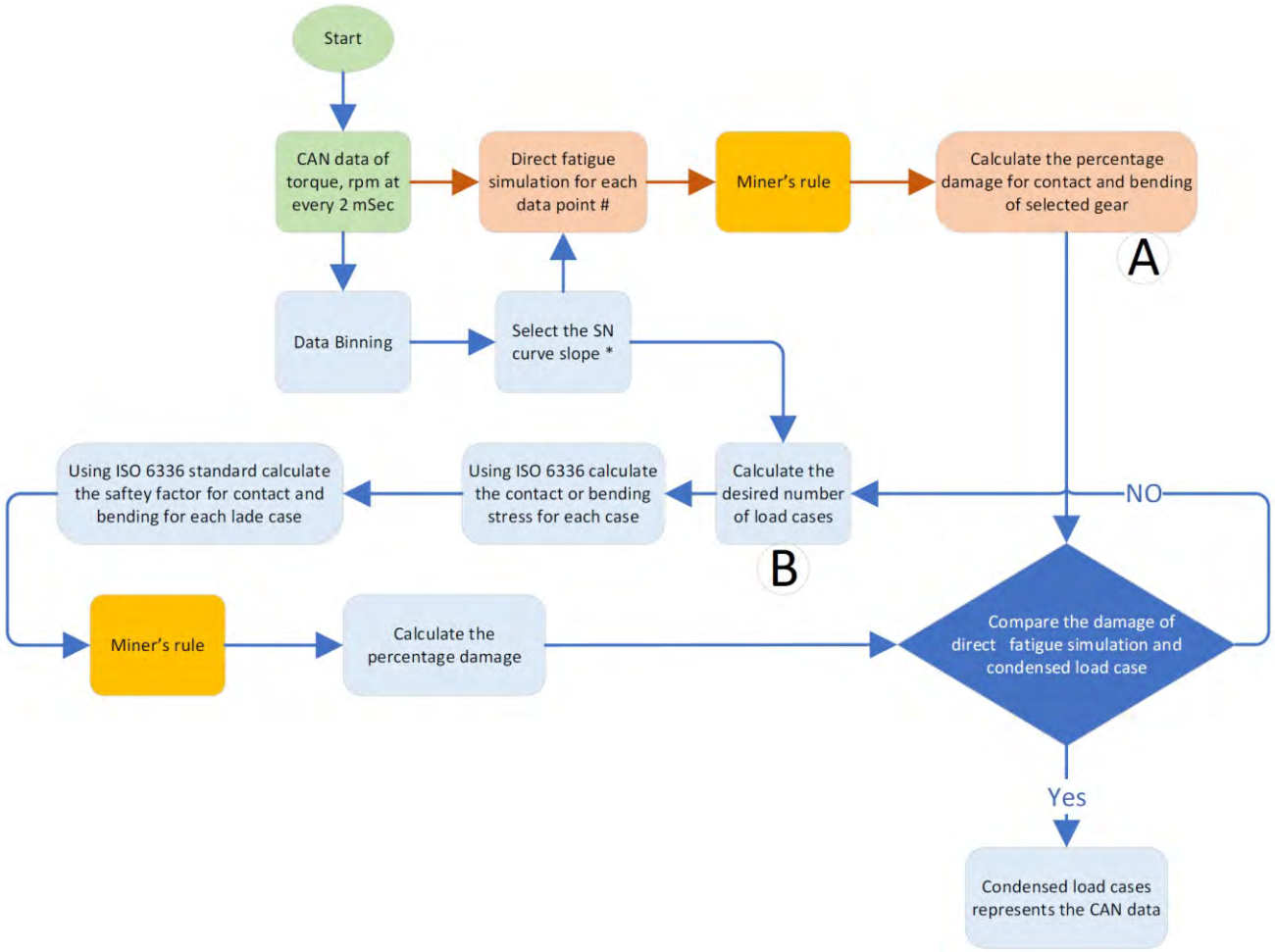

Figure 3 Summary of duty cycle condensation and remaining life calculation

	A	B	C	D	E
1	time / s	engine speed / rpm	output torque / Nm	distance / km	gear
2	11.866	1259.8	108.65	0.001	1
3	11.868	1261.4	105.212	0.002	1
4	11.87	1263	101.544	0.003	1
5	11.872	1263	98.106	0.004	1
6	11.874	1263	95.584	0.005	1
7	11.876	1263	93.063	0.006	1
8	11.878	1263	90.771	0.007	1
9	11.88	1263	89.854	0.008	1
10	11.882	1263	89.166	0.009	1
11	11.884	1263	88.937	0.01	1
12	11.886	1263	88.708	0.011	1
13	11.888	1263	87.333	0.012	1

Data continued

Figure 4 Sample Road load data which shall be similar to CAN data

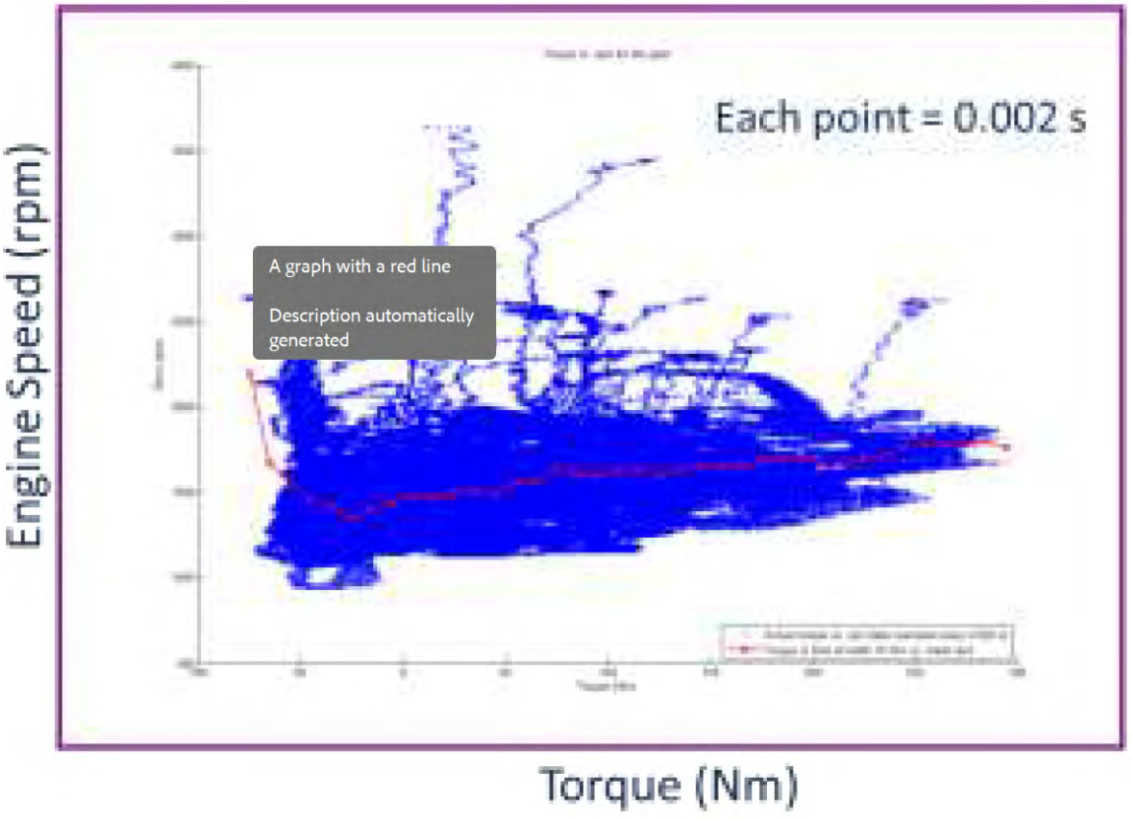

Figure 5 Assumed sample CAN data.

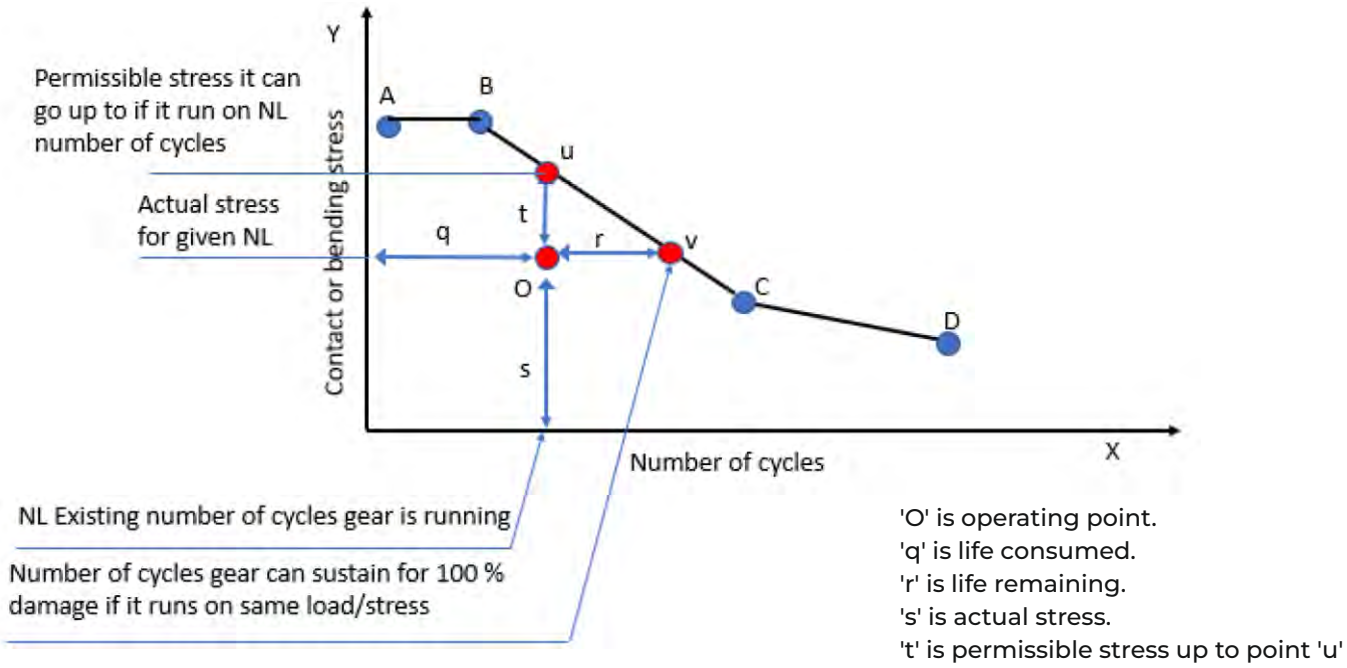

Figure 6 Operating point for the selected single torque against the SN curve.

is calculated for contact and bending using Equation 2The equivalent torque is calculated where P is the slope of SN curve and it can be

$$T_{eq} = \left(\frac{n_1 T_1{}^{p} + n_2 T_2{}^{p} \ldots\ldots}{n1+n2+\cdots\ldots}\right)^{\frac{1}{P}}$$

Equation 2

determined from the XY coordinates, i.e., coordinates of B and C if the operating points falls above C, and C and D points if operating point falls below C but above D in Figure 6. This equivalent torque is then used to calculate the contact and bending stresses using ISO 6336, DIN 3990 or AGMA standards. Then the stress is checked on SN curve as shown in Figure 6.

Figure 7 is a sample plot which shows the comparison of road load data done as direct fatigue simulation against the condensed duty cycle. Reference is taken from [6]. For the readers the summary of [6] explained below –

From Figure 6 the Percentage damage is calculated as q/(q+r) and if we sum up all damages for the load case we desired in block B of Figure 3 and equate it to damages calculated for millions of data points by using direct fatigue simulation in block A and if the damage matches then the block B load cases which are handful will represent millions of load case in CAN data. Doing this procedure for all gears and bearing with the respective slope chosen and converting the millions of data points into handful of load cases where the damage is same is called as duty cycle condensation.

The 'r' part is what we are aiming at, and it is calculated for each load case and based on which the remaining life is reported for complete duty cycle.

1.4 From safety factor to reliability

Now the question is, is it sufficient to have remaining useful life where we have merely the factor of safety over 1.0? It is not. Because we should know it in terms of reliability. A user wants to know the survival rate of subsystem or full system in terms of confidence to use it. The reliability analysis tells us that even if part has a factor of safety over 1.0 still there is some probability of failure before it reaches its intended life. The subsystem we are discussing

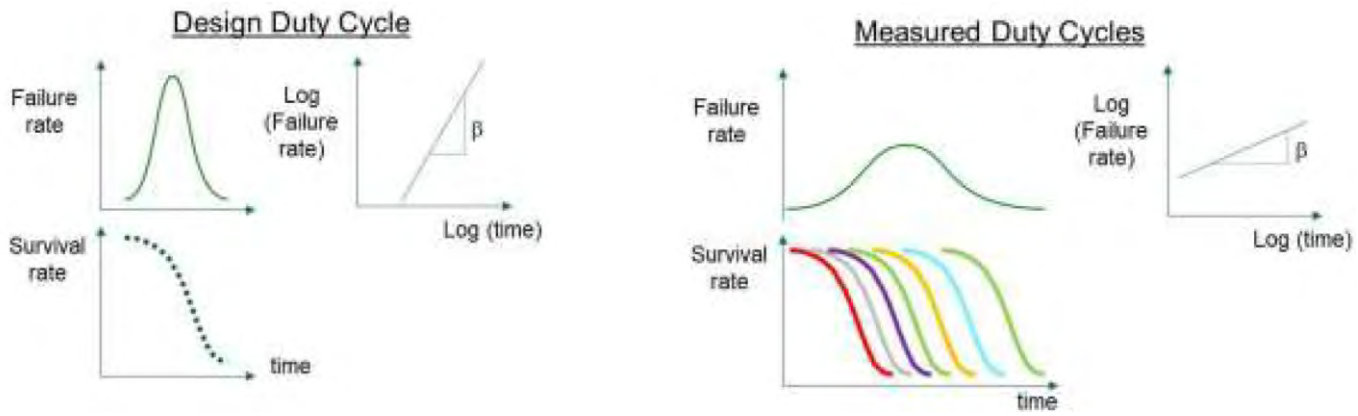

Figure 8 Variation in survival curves due to different loading conditions

here is the gearbox in aircraft either EMAGB or AMAGB all the gears and bearings will not have the same reliability and the lowest among them will decide the reliability of gearbox. There are some subsystems where there may be a situation where lowest reliable part may not be a critical part and system can still work even after its failure. Which is not the case in aircraft and gearbox fails if gear or bearing fails. Although there is always a redundancy in aircraft subsystems to safeguard the aircraft, but we are not considering those aspects here. Barry J et al [7] from Hexagon has published a methodology to and same is referred here. Barry J et al uses the Weibull distribution technique to predict the reliability. The digital proposed here is for aircraft whereas Barry J et al [7] have implemented the same for a tractor OEM and validated against the real life loading condition.

Barry J et al, [7] studied that there are challenges in using the Weibull distribution as the distribution shape which is vital parameter in prediction has a wide range and different papers use different values. Hexagon AB has conducted the study over ten vehicles to check this parameter. This study done over ten pilot lot vehicles shows that if we keep Weibull shape parameter constant there is variation in the survival curves and that is due to different loading conditions each vehicle experienced.

The process discussed above further refined and calculates the shape parameter and outputs the reliability. The same process is proposed here for aircraft gearbox.

The assumption used in applying the one single duty cycle for all the vehicles and predicting their reliability does not work. The Digital Twin proposed here with the real time data transfer to simulation model after every flight sortie into Romax Enduro and calculating the remining useful life along with reliability overcomes the assumption. The plot shows how gearbox reliability varies with shape parameter. It shows from Figure 8 and Figure 9that the reliability changes with the shape parameter and operating conditions. The shape factor is claimed with various values by various researchers, and it is confusing as which one to take. Dr Hein et al [8] collected the shape factors from various research done in one place.

1.5 Conclusion

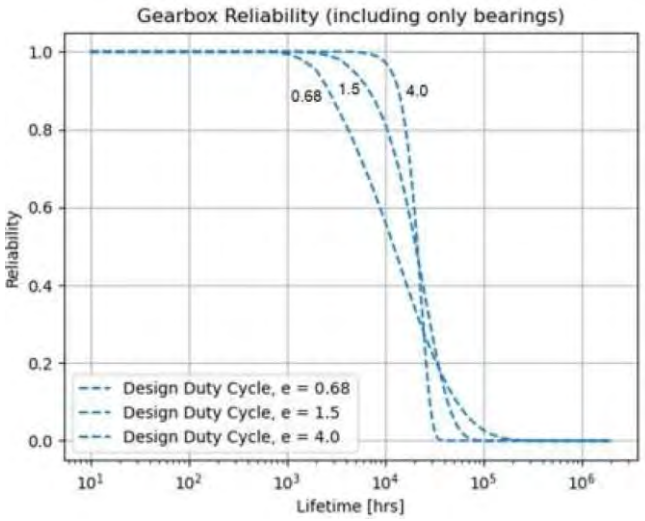

Figure 9 Variation in gearbox reliability against the shape parameter β

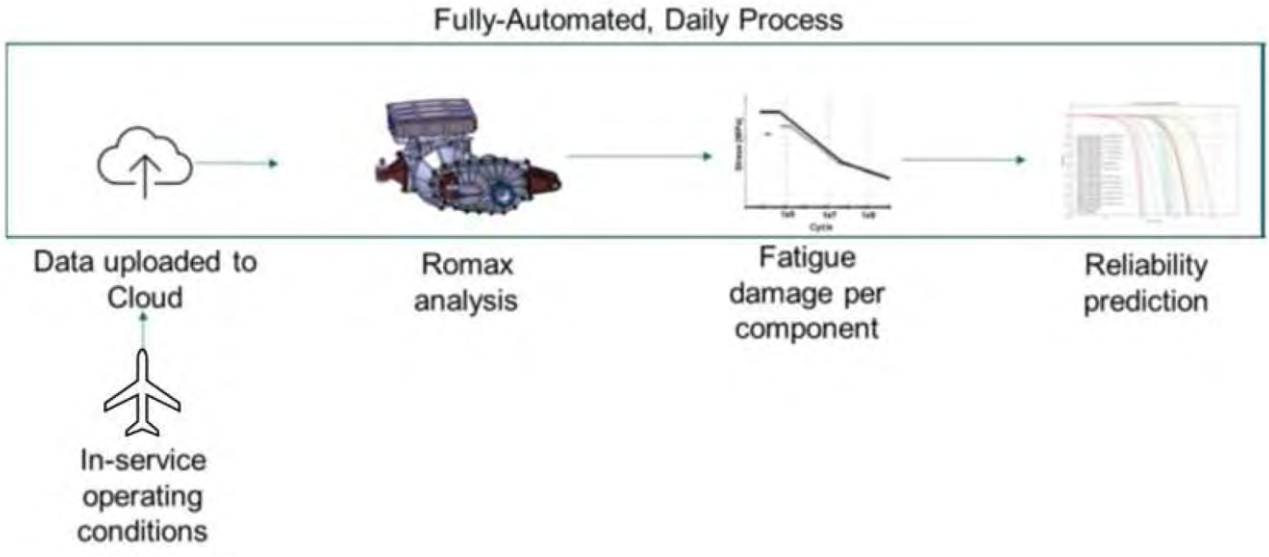

Figure 10 Overall Hexagon's proposed workflow to predict gearbox reliability

Variability in the operating conditions and variability in manufacturing and material data leads to unreliability.

The assumed design duty cycle is not the same as in operating condition and there is range of variation in material quality. The measured duty cycle gives more accurate shape parameter there by indicating accurate prediction of reliability in terms of remaining useful life. The prediction is not possible unless the measured data is transmitted through telematic system and associated with Digital Twin. The digital twin predicts the reliability, and the data can be further used for product improvement. The complete workflow [7] in collaboration with Hexagon's Xalt is as shown in Figure 10.

1.6 Limitations and further work

The current discussion is for gears and bearing only according to rating standards. The method is scalable to include various other physics and different analyses other than gear and bearing fatigue.

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Technical Publications for Indigenous Fighter Aircraft Programme – An SLM Driven Approach

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Abstract - There is a need for concurrent development of technical publications along with system development for an aircraft OEM to shorten delivery cycle time. Also, the aircraft owners/operators are adopting Enterprise Asset Management (EAM) systems for automation and paperless workflow in their operational, administrative and maintenance related activities. In the past, OEMs used to wait till certification (IOC/FOC) before taking up publication seriously because of the frequent product and process refinements during development. In addition, absence of robust change and configuration management for tracking variations lead to traceability issues, delays, errors, and rework for publication team. This paper brings out an approach for concurrent development of integrated technical publications facilitated through service BOM for deriving Aircraft Illustrated Parts Catalogue, Maintenance Manuals etc. in an enterprise framework of Service Lifecycle Management. This approach has been substantiated with the help of a case study where sample s1000D based publications were generated.

Keywords - Service Lifecycle Management, Technical Publications, Change and Configuration, Service BOM, Service Plan, S1000D

I. INTRODUCTION

Technical publications are major source of information for the operators that provide precise details about operation, maintenance, and repair of a product. Aerospace and Defence industry involve various stakeholders such as OEM, Design agencies, Vendors, Service Teams, Regulatory agencies who play an important role for efficient operations covering functional, technical and service aspects [1].

A. Types of Technical Pubications

A few widely used general technical publications are listed below in aircraft industry which facilitates for effective maintenance operations [1]

- Illustrated Parts Catalogue (IPC)
- Maintenance Manual (MM)
- Structural Repair Manual (SRM)
- Components Maintenance Manual (CMM)
- Engine Maintenance Manual (EMM)
- Service Bulletins (SB)
- Wiring Diagram Manual (WDM) etc.

A well created and managed technical publications are crucial for aircraft end users as it improves its operational availability, reduces product sustainment cost and more importantly build confidence of combat readiness by reducing turn-around-time.

B. Challenges

Military aircraft development programs typically will have a long product lifecycle and its complex service requirements demand effective collaboration across functional domains connecting all stake holders throughout product development as well as product sustainment phases. In addition, up-to-date and accurate technical publications are essential to ensure aircraft safety, reliability, efficiency and compliance with regulatory requirements. There are challenges such as capturing of as-built and in-service configuration, delays in communicating frequent design changes, use of multiple authoring tools and inability to re-use of information leads to inaccurate service documentation.

The objective of this work is to minimize the above gaps by inculcating change and configuration management concepts, re-use by data modules and S1000D standard data templates in an enterprise-wide Service Lifecycle Management (SLM) setup.

II. METHODOLOGY

For effective Technical Publications creation and updation, management of service data is crucial during aircraft Test and Evaluation phase. All service data such as service plan, service procedures, and skill levels, Ground Support Equipment (GSE) / Ground Handling Equipment (GHE) need to be captured during this stage in a centralised database. The data related to post servicing event are also crucial.

This database also captures key maintenance metrics like Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR), and Maintenance Man Hour per Flight Hour (MMH/FH).

A. Refinement of service business process

The following process and data model need to be refined for SLM driven technical publication:

- Role of Designers, Test Engineers, Service Planner, RAM Engineer, Product Support Engineer, Logistician and Publication Authoring Team in the collaborative framework
- Configuration Management of Aircraft Equipment Standard of Preparation (ESOP) [2]
- Traceability of embedded software version with installed equipment, sortie wise, tail number wise
- Management of substitutes for equipment and software tail number wise
- Traceability of equipment and tracking mechanism for life usage history of equipment [2]
- Establishing seamless user feedback mechanism interfacing SLM with operator's enterprise system

B. Establishment of SLM framework

SLM is the process of managing service aspects of a product, communications across functional teams and support overall product operations starting from design phases in an efficient manner with a main objective as maximizing product uptime. By enabling closed loop feedback from field to design and manufacturing teams, SLM provides a platform for product and process improvement to increase product serviceability and reliability [3].

1) SLM Value addition

SLM mainly focuses on handling data pertaining to product maintenance (Servicing Criteria, Service Procedures) & supportability (Skill, Support equipment) aspects as well as flight field data (Configuration data, installed equipment, Installed Software, Periodic check details etc.). It provides collaboration between designers & service engineers. It will collect service data (Includes spare parts, inventory etc.), field data and facilitates users to improve the product in terms of maintainability & supportability. The following are the SLM benefits:

- It facilitates capturing of all maintenance activities tail number wise
- Reduces time to convey the information to concerned stakeholders
- Cost effective product can be delivered to customer
- Early planning for servicing leads to reduce Turn Around Time (TAT) of aircraft
- Improves availability of aircraft
- Effective utilization of legacy data to improve

maintainability aspect of aircraft design for future programs [4]
- Feedback from customer can be captured for improving the design
- Share the relevant information of product while creating and updating of technical publications in electronic mode during product delivery

2) Configuration Management

Configuration &Change Management are core fundamentals of any SLM system. This will facilitate effective tracking of changes and the reasons in a closed loop environment. The BOM generated during design can be used to derive BOMs with different perspectives including service (SBOM) and publication (PBOM).

- Design changes are frequent. Recording the reason for changes & its corrective action attributes to develop knowledge bank for future programs.
- Each prototype is built with specific configuration to cover various test points & also frequent change of configurations will vary as per test objective. Managing this information is critical & complex [5].

3) Connecting Design, Neutral and Physical Structures

As-Designed Structure is a functionally organized structure system wise, which consists of parts, assemblies and equipment. It also includes important attributes such as part number, name, revision, manufacturer etc. Neutral structure consists of aircraft structure and its equipment which are to be tracked. The neutral structure also holds the alternate parts [6].

Physical structure is representation of an individual physical asset. First aircraft build is As-Build structure and as-maintained structure contains additional asset-specific information and records authorized differences from the product definition and captures characteristics, the history of the structural changes as it evolves over time and gets synchronize with the neutral structure amendments.

It will be helpful in tracking part utilization, part usage, and disposition history, manage physical locations and the assets in those locations as well as maintaining flight wise Serialized structure, recording snags (reported during filed or servicing) against individual physical asset.

4) Service Planning

It is imperative to identify the key factors that affect service events and resource requirements for efficient service activities. It is possible only such information captured staring from early design stages. Service Planning improves product availability by defining service requirements and frequencies [13]. In addition, it improves service performance with the help of service procedures based on fault codes captured. Service Planning enables

- Capture of baseline plans, workflows and its utilization [8]
- Import and export planning information with other systems
- Service work instructions including service procedures documentation (text, animations with 2D and 3D) [10].

5) Integrated BOM Management

Engineering BOM (eBOM) authored by designers created in Computer Aided Design (CAD) system grouped in function / system wise. Service bill of information is derived from eBOM as shown in Fig. 1 arranged based on serviceability point of view. Service plan is created for planning of service activities and service documentation such as Aircraft Maintenance manual (AMM), Aircraft Illustrated Parts Catalogue (AIPC) is resultant from service BOM and service plan.

6) S1000D

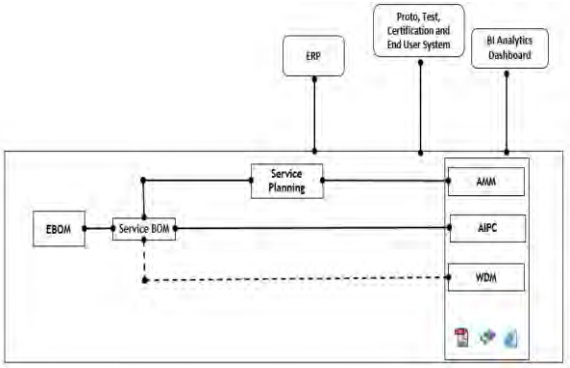

Fig.1. Service BOM and Service Plan connected

The main objective of S1000D is to support collaborative document development for various end users practicing different tools. Best results are achieved, by combining the SLM and Content management systems in an integrated setup connecting design, assembly and documenting complex aerospace and defense systems [9,12]. Fig.2 describes use of Data Modules and Common Source Database for generating S1000D technical publications as follows:

- S1000D benefits content creators and content consumers, enables faster product deliveries to maximize content re-use by introducing data modules
- Leverage common data source database [7]
- Modular documentation
- Provides graphics formats, structured text with reference and content usage guidelines [10]

III. CASE STUDY

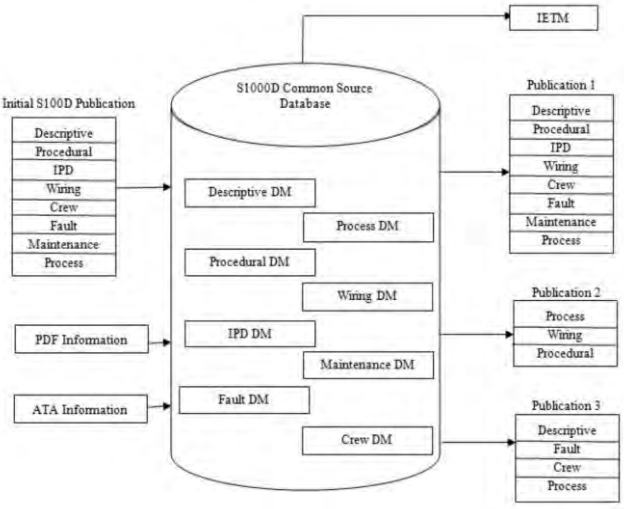

Fig. 2. S1000D Technical Publications using CSDB and Data Modules

A case study has been carried out where Service BOM is derived from engineering BOM which improves serviceability and precisely identify service needs by connecting service planning and physical structures [14]. ThisSLM ecosystem comprising integrated BOM, service plan, physical asset information facilitates up-to-date single repository related to technical publication.

A. SLM driven integrated technical publications

Indicative aircraft data is used to establish the methodology in S1000D framework. It consists of CAD design data and publication data in paper format. Existing PLM and SLM framework have been used and sBOM is created with end items, attachment as shown in the Fig. 3.The same is derived and re-organised from eBOM. Publication BOM is created by using data modules as shown in Fig. 4. The following are the main inputs considered.

- eBOMfrom PLM
- Existing AIPC, AMM
- SLM Modules
- Content Management
  - S1000D Template
  - IETM compliant tools
    - Rapid Catalogue
    - Rapid Manual
  - Rapid Developer

B. Change Management and Data Exchange

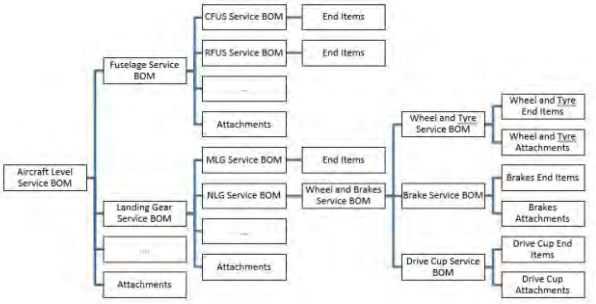

Fig. 3. Constituents of Service BOM

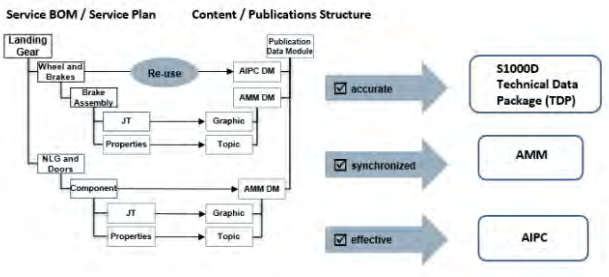

Fig.4.SLM driven integrated technical publications

Change management concepts are introduced with Problem report, analysis vis-à-vis requirement specification that are interconnected to data modules as described in Fig. 5.

The data re-use advantages are tapped in the

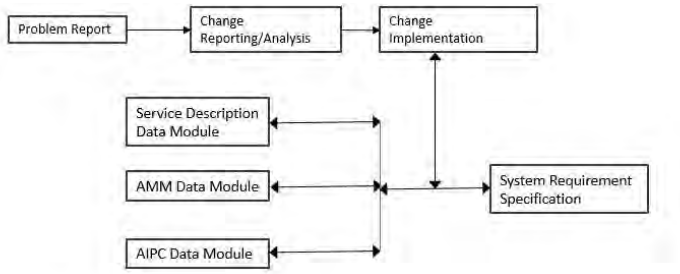

Fig.5.Change Management

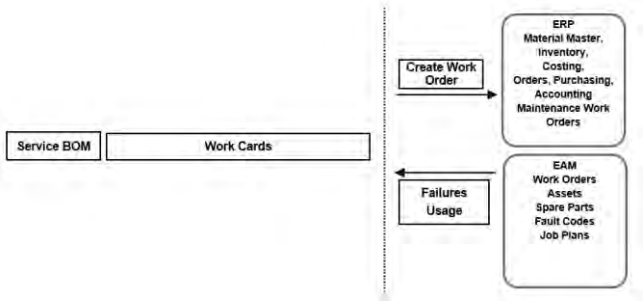

Fig.6.Data Exchange Between SLM and Other Enterprise Solutions

following areas:

- eBOM
- Part/ Equipment attributes(Part Number, Revision, Name, Description etc.)
- CAD and visualisation Files

It is imperative to facilitate exchange the data between SLM and other enterprise solutions to capture and process work orders, hazard notices, faults, characteristics, spare parts, job plans, inventory as shown in Fig. 6.

C. Key Success Factors Identified during Case study

The following Key Success Factors are identified during Case Study to be considered for successful implementation of full-scale project.

- Configuration management
- Create SLM Ecosystem
- Upgrade to stay current
- Dedicated SLM administrator and IT support team
- Adequate hardware software infrastructure
- Integration strategy
- Change management
- Continuous training and handholding

D. Risks Identified and Mitigation Plan for Proposed Fullscale Implementation

TABLE I. EVALUATION MATRIX

Risks	Mitigation
Selecting wrong SLM solution – Not fit for organization processes	Holistic approach, suitable to integrate downstream applications
Existing and New systems mix up	Study the new architecture and explore inbuilt functionalities
Poor integration	Seamlessly receive information from other systems
Unable to reach to different division	Expand the connectivity using simple web-based application instead of installation
Moving too fast	Incremental implementation
Users unwilling to use and share the data	Build new functionalities to cover various workgroups Conduct regular trainings / workshops
Migration of legacy data	Remove unused, duplicated data and introduce data templates

E. Proposed Fullscale Implementation

The case study is carried out using asmall assembly and needs enhancement tofull-scale up to aircraft level. It involves complete requirement capture, various environments creation along with legacy data migration, training and handholding as described in the Fig. 7

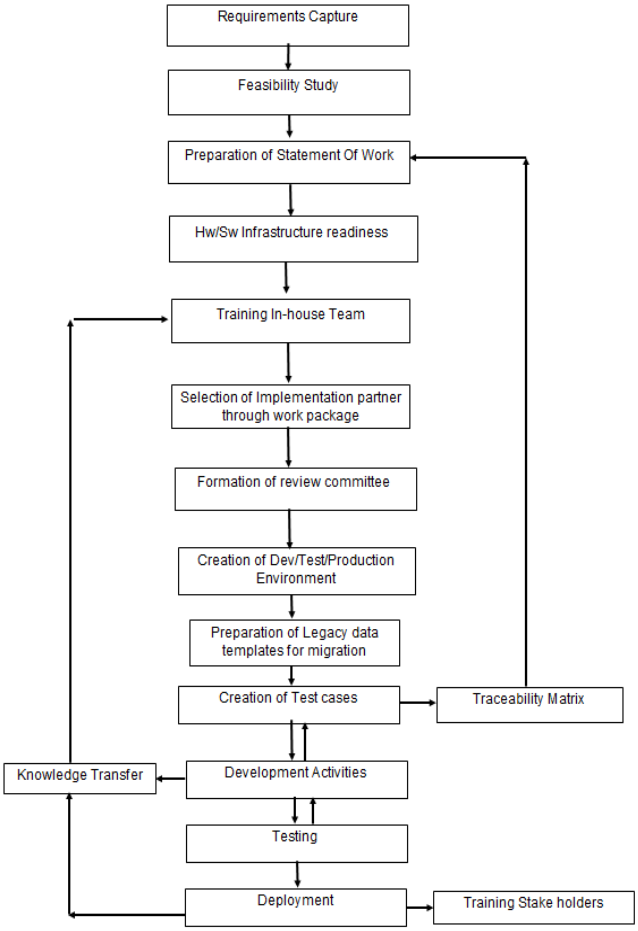

Fig.7. Proposed full scale Technical Publication Implementation

IV. CONCLUSION

SLM driven technical publication brings together service engineering, publication team and users at the early stage of product development and ensures single source of product knowledge using sBOM and Service Plan. Its inherent change and configuration principle makes it possible to customize publications based on aircraft configuration and users. sBOM also holds service-related information from suppliers, partners, vendors and OEMs which serves as a single repository of information for authoring publications. Methodology, Key Success Factors, Risk and Mitigation Plan to be implemented for full-scale technical publications are addressed as part of the case study using S1000D standard. It enables modularization, reuse and reduce the effort in exchanging the data.

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Availability Enhancement of Aircraft using Deep Learning Techniques for Unscheduled Maintenance

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Abstract - Availability of capital items is determined by down times due to maintenance tasks which directly affects LCC. While scheduled maintenance tasks could be optimized using Reliability Centered Maintenance (RCM), optimization of tasks pertaining to unscheduled maintenance needs careful attention, since randomness is involved. Offline Availability Centered Maintenance (ACM) is used to deviate from calendar time / usage-based maintenance, by incorporating suitable methodologies. In this paper, we propose application of Deep Learning Techniques to unscheduled maintenance activities by forecasting expected types of failures. Necessary ground support and logistics would be made available appropriately. Outcome of the technique presented here identifies types of failures expected and the number of inventories required to maintain desired availability.

Keywords - Availability, ACM, Deep Learning, Inventory Management, LCC optimization, MDT, MTBF, MTTR, RCM, PdM.

I. INTRODUCTION

On-demand availability is one of the critical parameters for all the items, especially for the capital intensive and safety critical items. Improvement in availability is typically achieved with Reliability Centered Maintenance (RCM) using qualitative closed loop design iterations. RCM also optimizes maintenance tasks by continuously monitoring and updating reliability data available from the field. This approach often results in detailed off-line analyses of observed failure mode. Maintenance tasks are eliminated / added based on the snag data analyses. This off-line analysis requires enormous time, cost and resources. In most of the cases, RCM is effective only to handle scheduled maintenance tasks, which are predominantly dictated by mechanical systems or components. However, for electronic products, effectiveness of RCM is minimal. For quantitative outcomes and results, Availability Centered Maintenance (ACM) was later proposed, especially in the aircraft industry. ACM also aims to improvise availability of the platform, by suitably altering maintenance planning, scheduling, frequency and spare parts optimization.

In both RCM & ACM, snag and maintenance data are utilized to optimize the tasks and reliability. Time to failure data is not used as a reference for any design or maintenance improvements. Usage time (execution time) plays vital role in determining deterioration of any components. The present approach aims to utilize time to failure data and propose a methodology using Deep Learning techniques to predict impending failure types. Using this data, the ground support team can quickly prepare for maintenance actions as required, so as to enhance availability.

II. APPROACH

Technological advancement coupled with industry 4.0, and continued development in data analytics have made the generation and analysis of large amounts of data more easily available and affordable. This large amount of data on maintenance could be utilized to modernize/ optimize maintenance strategies, such as switching from preventive maintenance to predictive maintenance. Research on developing data-driven predictive models using maintenance data for condition-based maintenance is required to be accelerated. In case for certain context, it is crucial to forecast the failure in timely manner and thereby taking preventive actions to avoid failures. Using deep learning techniques, it is possible to generate exact predictions of easily avoidable system failure. A system can be kept from malfunctioning by scheduled maintenance and evaluating the performance of certain components and pieces within a machine. Such predictive maintenance can prevent accidents, and failure of mission-critical systems exposing people and resources to risks. While periodic maintenance based on gross assessment and part life cycles is currently the most popular technique for preventing sudden failure, it cannot guarantee that a system will not fail before the threshold time for periodic maintenance.

Scheduled maintenance requires nothing more than an informal mathematical computation on when the system conditions demand repair or even replacement so that maintenance can be performed precisely and effectively. Deep learning-based ACM seeks to identify patterns in system failures by learning from past experience or historical data. We propose to use Deep Learning techniques on the failure data observed from the field so as to optimize maintenance tasks and reduce down times.

RCM ensures that all systems run at optimal efficiency and accuracy. It borrows from preventive and predictive maintenance modalities to guarantee each piece of equipment individualized attention aimed at keeping it functional. When implemented properly, RCM programs save money, improve safety, and enhance machine performance and reliability.

III. LITERATURE SURVEY

Reliability centered maintenance is coherent and rational approach to the idea of preventive repair program on the basis of decision tree [1]. The process starts at identification of the systems, subsystems and equipment for which certain maintenance procedure is required. RCM was introduced in aircraft systems because there is a requirement of high level of safety. The main part of RCM is understanding the function of a system in turn understanding the functional failure and also unacceptable degradation level. Initially RCM is predominantly utilized in the case of aircraft industry and later incorporated to other industries [2]. RCM provides a structure for improving operations in a more systematic way. The need for reliability models and data are stressed upon. Several military and non-military standards have also been published under RCM.

A necessary basis for proceeding with the result of RCM analysis is that the organizational and technical maintenance support functions are readily available [3]. A major issue is therefore to ensure the availability of the maintenance support functions. The major part of the approach is the use of generic RCM theory and also time for maintenance. RCM is mainly designed to reduce the costs by finding a balance between higher costs against the cost of preventive maintenance. It is a compromise between soft life and hard life to optimize the overall cost. Hard life is the age or time interval at which the component has to be definitely replaced.

Enormous potential for machine learning and deep learning have risen due to the ongoing digitization of industries to 4.0. New technological possibilities are emerging that contribute to strengthen the field for competitiveness. Machine learning methods such as regression analysis that detect linear and quadratic correlations and models that can handle complex and non-linear estimations [3] are often used. The main consideration for evaluation of AI based solutions

are human injuries or fatalities, negative health effects, environmental damage, loss of system effectiveness and material loss or equipment damage [4]. A proper equilibrium between frequency of maintenance and cost is required to be ensured [5]. RCM is an upgraded analytical version of preventive maintenance. As it symbolizes, reliability is the main point for maintenance planning. The main purpose is to reduce the cost and increase safety and reliability. Reliability and the peculiarities of system items are examined to determine suitable maintenance tasks and time periods. Over the years, RCM has gained a solid reputation for being a successful method, but also for having some shortcomings. One of these is traced to the limited assessments of risk and uncertainties.

As the number of industrial data increases, deep learning driven predictive maintenance solutions that assists and optimize maintenance tasks have become popular. This aims to facilitate this task by studying state-of-the-art deep learning architecture and how they can be integrated into predictive maintenance phases to meet the needs of industrial enterprises. Machine learning research trends are moving towards more complex models such as ensemble methods, this is because deep learning is more accurate when working with large datasets [6]. These techniques have evolved with increasing computing power, the latter mainly with the development of GPUs. These models achieve a state-of-the-art results in many areas, such as intrusion detection, computer vision and speech processing. The development of hardware, data analysis and intelligent algorithms transform traditional manufacturing systems into highly intelligent and autonomous manufacturing systems. It enables self-organizing operations and self-adaptive collaboration for complex and dynamic production activities. A study of predictive maintenance using ANN in an intelligent manufacturing system [7]. The fault prediction accuracy is very high while comparing with traditional methods. For DL, the reliability data forms the basis for time between failure predictions [8]. The component reliability is completely studied and enriched for obtaining the time between failures. The neural network is used for final value prediction for the most efficient maintenance. The proper implementation of RCM via accurate prediction of the failure time, the most efficient maintenance strategy can be determined. The component reliability is completely studied and enriched for obtaining the time between failures. The neural network is used for final value prediction for the most efficient maintenance. The proper implementation of RCM via accurate prediction of the failure time, the most efficient maintenance strategy can be determined. The exponential distribution cannot be used to simulate products that fail due to wear or any other mode connected to their age, which is a fundamental flaw to the entire RCM idea. The ideas of soft life and hard life are used in a novel RCM strategy that aims to reduce overall maintenance costs. For ease of understanding, each component is simply given one possible cause of failure[9]. The model, however, is easily adaptable to other failure types.

To comprehend the crucial function that logistic assistance plays in maintenance practice, studies of the subject have also been conducted. The exploration of the potential uses of existing data for improving maintenance processes and, in some ways, also spare parts delivery, has been the focus of this study due to the broad issues of maintenance[10]. The maintenance techniques are the subject of the investigation. The aerospace engineering disciplines' views on health monitoring have radically changed over the last ten years, with a focus mostly on the quick development of artificial intelligence. The next gen health monitoring system, also known as Prognostics and Health Management, has an emphasis on proactive condition-based maintenance, forecasting, and prognostics, as opposed to traditional health monitoring practices, which are centered on planned and preventive maintenance[11]. Regression-based cost estimating techniques are still widely used to make investment and technology decisions. Despite being simple to use and quick to create, they have a number of restrictions that affect both their temporal and universal applicability. While

some of these issues have been addressed by current research and development in this field, aeronautical engineering still lacks a flexible and adaptable valuation framework[13]. Although great progress has been made in tackling ANN application obstacles, several issues, such as whimsical orientation, need to be overcome. Other issues include rule and template matching, object categorization, location, scaling, and neuron behaviour analysis in hidden layers[14]. Additionally, it appears that research emphasis and advancement in the subject are slowed down by the paucity of existent literature on the problems related to ANN application to pattern recognition. Deep learning has been coordinated into different subject fields as of late, permitting the revival of fields that had recently arrived at their advancement limits. Deep learning has picked up speed in applications including picture handling physical science and regular language handling. Furthermore, it is being utilized as an establishment to quickly foster custom modern applications. Deep learning is the most common way of learning the characteristic regulations and portrayal levels of test information and consolidating low-level elements to frame more conceptual significant level portrayals of quality classifications or highlights by building a brain organization[15]. It can imitate the way of behaving of the human mind during the time spent logical figuring out how to find disseminated include portrayals of information, permitting complex learning errands, for example, order to be performed with basic models.

Maintenance aspects should preferably be considered during system design, from early concept states. Even though maintainability constraints are usually not considered at the initial stages of development. But detailed maintenance strategies should also be considered before the system is put into operation. After system is put into its operational phase, maintenance activities are required to make sure its performance is unaltered and as intended by the design so that the aircraft can achieve high reliability and availability. The present paper proposes utilization DL algorithms to forecast expected type of failure along with time to failure.

IV. OVERVIEW

With recent trends in systems and applications, real-time fault detection alone is not sufficient to ensure aircraft safety. Prediction is needed to acknowledge the user about the aircraft condition. One is to estimate the time to failure and then to estimate the type of failure so as to get whether there is enough time for utilization or replacement. The Fig 1 depicts classical maintenance strategy.

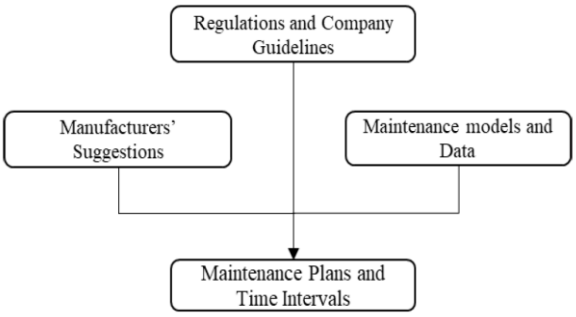

Fig 1: Classical Maintenance Strategy.

RCM solutions have to deal with many factors, peculiarities and challenges data. Desirable properties for a predictive maintenance system are:

- quick detection and diagnosis
- isolability (distinguish among different failure types)
- robustness
- novelty
- identifiability
- classification error estimation
- adaptability
- explanation facility
- minimal modelling requirements
- real-time computation
- storage handling
- multiple fault identifiability

A. Stages Involved in Reliability Centered Maintenance

Most of the deep learning techniques for availability enhancement and maintenance are having the same principle as that of other machine

learning and statistical techniques. Predictive Maintenance uses specific set of steps involved in such a way that decisions and algorithms followed in each stage will influence the succeeding ones.

- Preprocessing: In this step the attained data is prepared for further stages. The failure time data which are sampled at different dates according to the test conducted by using different platforms to create a time series data which is easier to handle. Data cleaning drops or extends to not available and missing values, oversampling is applied data imbalance to increase the accuracy on most scarce failure datasets, change features by interpolating o new space where it is easy to handle by the model.
- Feature Engineering: In this step an extraction of certain required features so as to serve as input for further steps and thereby boost model performance is carried out. Feature extraction uses statistical measures in time and frequency domains. Principal component analysis, concatenation and fusion methods are used to create new features by combining available ones.
- Anomaly Detection: Through this step it is seen whether the system is working under required circumstances or not. Anomaly detection requires preprocessed and in certain cases of feature engineered data. After preprocessing and feature engineering the dataset is split into train and test sets and optimize it for model analysis.
- Diagnosis: Whenever an anomaly is detected the next step is to understand whether it is created because of some working pattern and then can evolve into some future failure situation or it does not create any problem for the regular working of an aircraft. The algorithm proposed should be relevant for the problem addressed which involves multiclass classification clustering. The dataset chosen has different failure types, failure and non-failure recordings. The main aims is to calculate the asset damage or deviation from current working condition and historical data under supervised condition. The diagnosis step becomes easier as the number of data available for model formation increases.

B. Analysis

Unscheduled maintenance (caused generally by electrical and electronic based products) often poses challenge to bring the system back online and serviceable, due to the fact that exact time to failure of products are neither known nor approximated. Since time to failure is statistically distributed, it is not possible to latch on a fixed schedule for maintenance of these kinds of products. Hence provisioning of inventories would be unpredictable and time varying. Conventional spare parts provisioning using birth-death queening process assumes constant arrival rate, repair rate, queueing delay and logistics delays. From the practical experience, it is observed that, the assumption of constant failure rate does not hold good. Hence, we propose deep learning of failure data in determining time to failure, types of failures and forecast expected maintenance requirements. Fig.2 flowchart depicts our approach.

For the purpose of applying deep learning techniques for the current problem at hand, it is essentially required to categorize type of failure by categorically analyzing data. Snag data reported are to be analyzed off-line critically in order to find out root cause of observed fault. Several activities of troubleshooting are usually carried out on the platform as well as various applicable test rigs to reproduce the fault, on ground. Detailed design analyses shall be carried out to find out logical reasoning and root-cause. Failure analyses of defective components are also carried out using non-destructive and / or destructive testing. From detailed design defect diagnosis and investigation (termed as *D⁴I*) root cause was identified and eliminated for each of the observed fault by possible design corrections, maintenance tasks or pilot operating procedures. Those failure data are utilized for the purposes of analysis. Classification of type of failure is carried out to identify whether observed failure belongs to hardware failure, software failure or hardware-software interaction failure. Although, this classification is not just as easy to segregate data into different bins, *D⁴I*

analysis would aid in correctly classifying each of the faults observed. Time to failure data required to be obtained.

V. METHODS FOR MAINTENANCE

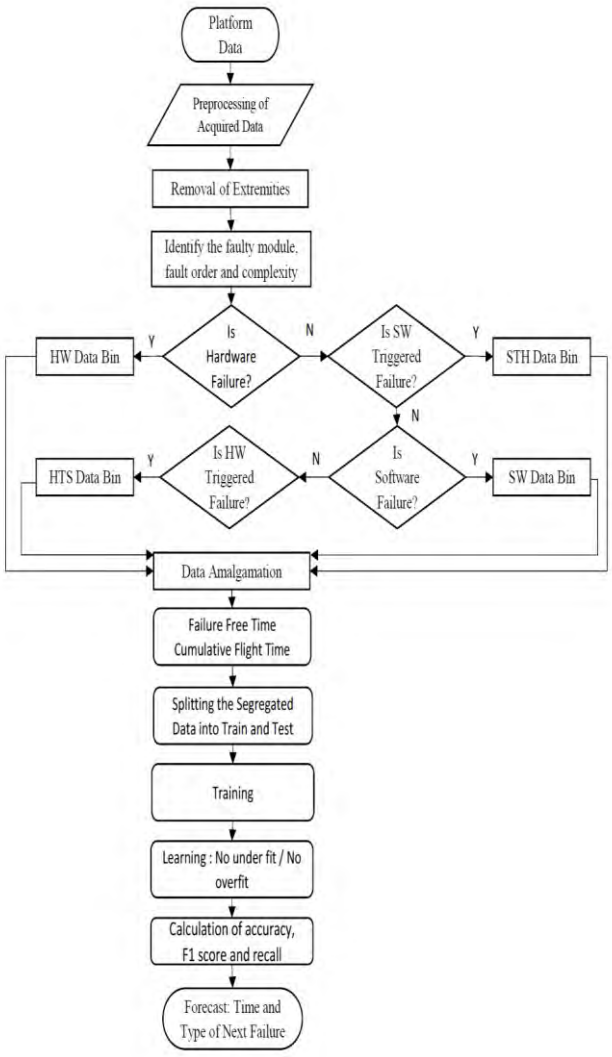

Fig 2: Methodology Flowchart

There is no universal approach to maintenance. To develop a maintenance strategy one has to evaluate and weigh the unique benefits and shortcomings of each strategy, depending on what assets are involved, stages of reliability journey, and the impact of downtime at the platform/facility.

A. Reactive Maintenance

Also known as breakdown or run-to-failure, reactive maintenance is about fixing things when they break. Since repairs are not planned, it's a good method to employ for equipment that is not essential for operations or has a low cost. While it requires minimal planning, the drawbacks of reactive maintenance can be substantial if it's not carried out correctly. If the approach is used for all equipment, there can be huge delays in production when a critical piece of equipment fails. Further, if right parts and supplies are not available on hand, the costs for rushed shipping can become significant. In short, reactive maintenance often means more downtime and higher maintenance costs when it's not used strategically.

B. Preventive Maintenance

Also known as proactive maintenance, this method involves periodically taking assets offline and inspecting or repairing them at predetermined intervals (usually time or event-based triggers). The goal of this approach is to extend the useful life of an asset and prevent breakdowns from occurring. Many organizations employing preventive maintenance use CMMS software to trigger work orders when a PM is due. This allows a facility to automate much of its scheduling efforts, which is a key ingredient of this preventive approach. Because planning is done in advance, it's much easier to have the right parts and resources on hand to complete each task. As with all maintenance types, there are potential drawbacks to relying solely on preventive maintenance. If the PM schedule isn't regularly monitored, audited, and improved, "PM creep" can occur. This is when technicians get bogged down by unnecessary tasks and cost the organization time and money. Similarly, performing too many PMs can open the door for post-PM breakdowns. The risk gets higher as PMs get more frequent.

C. Predictive Maintenance

Predictive maintenance (PdM) aims to predict failures before they happen so maintenance can occur at just the right time. PdM uses data from machine sensors and smart technology to alert the maintenance team when a piece of equipment is at risk of failing. For example, a sensor may use vibration analysis to alert the maintenance team that a piece of equipment is at

risk of failing, at which point it will be taken offline, inspected, and repaired accordingly.

It is possible to carry out PdM via visual inspections of equipment, but the easiest way to establish a predictive maintenance strategy is by using a CMMS to track meter readings. The advantage of PdM (over PM) is the potential for cost savings from reduced man-hours spent on maintenance, and more insight as to the performance and potential issues arising with the machine. Additionally, a reliance on data and sensor information means maintenance is determined by the actual condition of equipment, rather than a best-guess schedule. Of course, relying so heavily on data means that there is a higher up-front cost to ensuring this maintenance approach can thrive.

D. Reliability Centered Maintenance

Reliability-centered maintenance (RCM) addresses the fact that occurrence of failure is not always linear in time domain. RCM is a highly-involved process that seeks to analyze all the possible failure modes for each piece of equipment and customize a maintenance plan for each individual machine. The ultimate goal of RCM is to increase equipment reliability. RCM is considered complex because each individual asset must be analyzed and prioritized based on criticality. The most critical assets are those that are likely to fail often or will result in large consequences in the event of failure. Because each piece of equipment is analyzed on its own, it's possible that the end result of embarking on an RCM effort is having as many different maintenance plans.

Brief summary of each of the maintenance methods is summarized in the table above.

VI. ANN ARCHITECTURE

Artificial Neural Network (ANN) provides a solution for complicated network pattern problems both in categorical and time-series types. Discriminant analysis is generally used for statistical analysis but the predictor variables need to be multivariate normally distributed. ANN is compatible with a wide variety of problem types both linear and non-linear. Neural networks are majorly two categories one with binary-valued input and the other with continuous-valued input. And these can be further divided into supervised and unsupervised learning algorithm. Neural network applications are presented as mysterious object that determine complex patterns in data.

It is necessary for the developer to specify the input

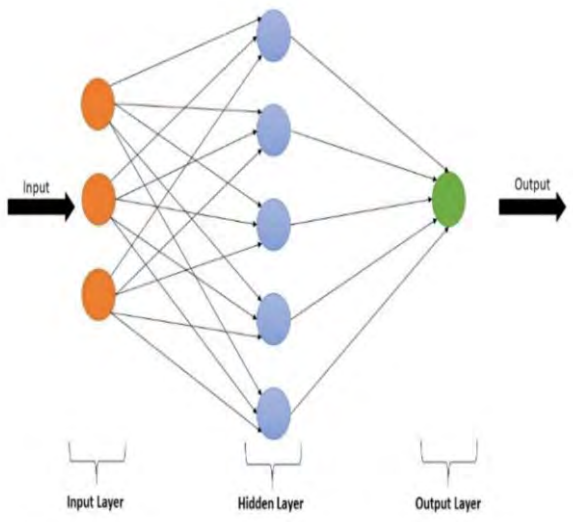

Fig 3: Basic Structure of Artificial Neural Network.

TABLE I. Maintenance Methodology Comparison

Strategy	Idea	Cost	Pros	Cons
Reactive	Fix it when broken	Low	Suitable for minor equipment	Can lead to runway of repair cost
Preventive	Scheduled maintenance	Average	No expertise required	Without optimization creep can occur
Predictive	Condition based monitoring	High	Timely maintenance	Can be expensive
RCM	Determination of best maintenance strategy	Highest	Proper execution provides max. efficiency	Requires time and data for proper execution

values, training and test data set sizes, learning algorithm, network architecture and transformation function. Some of these specifications depend on each other. A proper methodology is to be followed for precise ANN approach and it is given as follows:

- Acquiring the data to be used.
- Procurement of input variables.
- Segregation of given data into test and train sets.
- Define the network architecture.
- Determination of a suitable learning algorithm.
- Transformation of variables into required input.
- Train the algorithm according to the data used.
- Use the test data to validate the trained algorithm.

ANN is a precious tool for modelling non-linear systems or data, especially when there is a confusion in the pattern of the data. The designing of ANN is a tedious process as there exists lots of alternative. Also the selection of the size of test and train sets are also challenging as it changes the general performance of the designed model. A minimum of [2] years of data is considered to a nominal starting point for proper time series models. These are considered to be improved if more and more data is added to the set. ANN will be mainly focused on feed-forward supervised learning.

Artificial Neural Network follows certain optimal design. ANN these days have been implemented in wide variety of applications such as engineering, business, medical and scientific problems. Through researches it has been proven that ANN has shown its dominance over traditional statistical methods and also standard machine learning techniques. ANN forecasted models have achieved accuracies of [60]% and are mostly used for forecasting financial time series. The most crucial demand for artificial neural network is the selection of proper input variables and acquiring sufficient amount of training set in order to appropriately model for the application. An accurate neural network modelling and designing is a complicated process. Selection of sufficient training set is a primary challenge. The ultimate performance of the designed model becomes better as the number of inputs increases. Following subsections explain the rationale for our selection of ANN to solve the problem at hand.

A. Selection of Inputs

All artificial intelligence platforms are highly dependent on input specifications. The belief that ANN performance will increase as the number of input variables is true but addition of misspecified input credentials may lead to prediction of a bad model. Noise input variables produce poor generalization of ANN performance. Both under and over specification of input variables cause suboptimal performance.

There can be mainly two approaches for input variable selection in supervised learning neural networks. Firstly, the weights assigned to each input variable can be adjusted for a better approximation for the desired output. The technique involves the weights approaching zero for those variables that are non-significant. The second is that there will be weighted values will never be zero rather there will some contribution to the output of the neural network. Highly correlated variables should be avoided from the input vector because it multiplies the effect of those variables and leads to noise in the output variables. The optimal set of input is defined by performing standard knowledge acquisition by which there is a guarantee that the input variable is not underspecified.

B. Learning Method Selection

After determining the suitable input variable, a proper learning method should be identified for model categorization and time-series problems. Learning methods can be classified as supervised and unsupervised. Both require a collection of training data that enable ANN model to produce the required output. Supervised training requires the output at the time of training, whereas in case of unsupervised there is no requirement of output data while training, therefore unsupervised training has less complexity and accuracy compared to supervised.

- Unsupervised Learning: In this unsupervised

learning each input categories are fed to the learning ANN and distinct input vectors are formed and reformed as new and new inputs are created. The next stages are formed on the basis of how each new example matches with the existing one. The hidden layer which is usually called F^1 is same as the number of input layers and serves as the feature detector. The output or F^2 layer is defined by number of categories to be defined.

- Supervised Learning: It is a type of back-propagation learning algorithm and one of the most popular choice for implementing artificial neural networks. This algorithm is useful for most commercial neural networks and is widely accepted due to its versatile nature. Under various research it has been shown that back-propagation trained ANN are able to manage or learn arbitrary category mappings. It is superior to other methods while the data provided with sufficient number of noise or error-free training samples.

C. Architecture Design

The architecture for ANN includes a number of layers of processing elements or nodes, these include input layer, output layer and any number of hidden layers. Design of hidden layers depends on the selected learning algorithm. Supervised learning algorithm is more flexible in the design of hidden layer. An ANN without hidden layer is also possible but this is will be a linear separable, which limits the application. ANNs with multiple hidden layers have the capability to be robust with complex and nonlinear systems. The number of hidden layers depends on the complexity of the problem. ANNs with single hidden layer create hyperplanes, ones with double hidden layers combines hyperplanes to form convex decision areas and those with three hidden layers combine convex decision areas and form concave regions. As the number of hidden layers increase there exist a trade-off between smoothness and closeness-of-fit.

Greater the hidden layers closeness of fit and lesser means the smoothness will be improved. Researchers have shown that single hidden layer with large number of hidden nodes in a single layer has the capability of modelling any categorization mapping. Therefore, domain problems that have a standard nonlinear equation solution are solvable by a single hidden layer ANN. Number of nodes is determined by trade-off between training time and accuracy of training i.e., as the number of nodes increases the time of computation increases. Also it was proven that ANNs' performance was found to be poor until there is sufficient amount of hidden units in order to correlate between input vectors and also for the desired outputs. On the other hand if the amount of hidden layers is increased there will be proportional increase in time of computation but no significant rise in accuracy is there to be pointed out. As discussed knowledge acquisition is required for optimal input variable for ANN system utilization. During this phase the decision factors and additional engineering knowledge is used for computing the number of hidden layers and nodes. There exists an approach for automatic calculation of hidden units and the steps are follows:

- At first, the neural network architecture is created with very small number of hidden units or with very large amount of hidden units.
- Train the network for a predetermined number of epochs.
- Evaluate the error in the output nodes.

If the error exceeds the desired threshold value, then a unit is added or subtracted, and the process is continued until the error is brought down the threshold. The knowledge attaining process for ANN designing requires clustering of domain experts. Further the analysis of decision factors is used for configuring the optimal number of hidden layers for efficient modelling of the given problem.

D. Acquisition of Training Sets

The generalized belief is that the performance of the designed model will increase as the size of the training quantity increases for time-series applications. Accordingly the designer must acquire maximum possible amount of data as

possible for optimal design of the neural network. A minimum number of training data required is four times the number of weighted connections contained in the network. Another factor to be considered is how well the provided data is based on the real world samples. If the training samples deviate from the real-world instances then the clarity in the estimated model will also reduce. Therefore a proper understanding is required in order to attain distribution on upon which the network is working.

The training set of an ANN should be identity of the majority of the population. The training should be started with less number of data and step by step addition of data is to be done until there is a decrease in performance of the neural network. The quality of the neural network forecasted outputs get effected by the training data and is called the time-series recency effect. The time-series (TS) recency effect states that for the time-series data, model construction data that are closer in time to the values to be forecast produce better forecasting models. It can be said if the data used for forecasting are closer to the date of forecast then the model produced will be of higher quality.

Initially, ensure that the input vectors selected captures all the required criteria proposed by the domain and also eliminate correlated variables. Thereafter, suitable learning neural network algorithm is to be selected depending on the constraints imposed by the training set provided. Finally, the architecture of the hidden layers is determined by further analyzing a domain expert's clustering of the input variables or heuristic rules for producing an output value from the input variables. The collection of clustering/decision heuristics used by the domain expert has been called the set of decision factors. The quantity of decisions is equivalent to the minimum number of hidden units required by an ANN to correctly represent the problem space of the domain.

Therefore the basic idea for designing the ANN

- Extensive knowledge acquisition: Targeted at identifying the required domain information and also recognizing the decision factors from the domain for finding the solution for the problem to be modeled.
- Eliminating noise variables: Identifying and removing noncontributing variables, keeping only the required correlated variable depending on the data type and distribution.
- Selection of suitable learning method: Implementation of supervised learning method according to the data provided.
- Splitting into training data: The data required for efficient training is four times the number of weighted connections.
- Determination of number of hidden layers: the number of hidden layers required is mainly analyzed by the complexity. Usage of single hidden layer is possible and adequately selecting the nodes to model.

VII. METHODOLOGY

In the present case, it was decided to predict future failures and types of failures. This will enhance preparedness of maintenance tasks/teams/resources, so that there is only minimal down time. The scenario discussed is the forecasting of failure data of a platform for adequately maintaining the inventory for effective replacement and continuous working.

For this purpose, an electronic equipment which is complex in hardware and highly intensive in software is chosen. Since, failure of this system can happen at any time, when such a failure occurs the availability of a replacement unit is a must for avoiding any delay in the process being carried out. Also each product or component has its own life-cycle therefore storing the component for a large time period expecting a failure without any definite prediction of the time of failure will burden the stores and LCC.

Periodic maintenance is not adding any improvement in inherent reliability of electronics equipment, since it conforms to exponential *pdf*. The proposed approach is intended to generalize and characterize life distribution of electronic equipment.

In our case the data available is taken from testing at different phases of equipment on the platform. Other testing data such as ground test, system test, integration test are ignored, where operating environment is different than the platform operating environment. The chosen equipment data pertaining to [10] years of usage has been considered.

Since failure of the equipment on the platform cannot be determined by any specific criteria as such, the only factor available is the date on which particular failure occurs and its reoccurrences. Also failures do not follow a definite pattern. In order to consider for failure the study has to be conducted on the basis of the continuous whole ten years rather than specifying on a certain date. In the acquired information the dates specified are only the dates on which a failure has occurred. This failure has been divided into four categories: Hardware failure, software failure, hardware triggered software failure and software triggered hardware failure.

The requirement is to predict on which specified date a specified failure might occur so as to make the component ready for replacement. Hardware Failures or faults whose root cause could be isolated to hardware malfunction. Temporary upset and permanent latched failures of hardware are accounted as root cause. Software failures are expected when there is a deviation from the desired functional requirements, incorrect sequence of operation, untimely execution of command, improper usage of variables. These errors could result into faults and failures. Hardware triggered software failures occurs when a hardware could make the software component unserviceable, if these failure cases and modes are not contemplated a-priori during design stage of software. A systematic analysis of observed fault or failure would aid in narrowing down this mode of interaction failure. Software triggered hardware failure happens when there is an incorrect implementation of software logics, which is not compatible with chosen hardware components. If this state is detected, the system could transition to fail-safe state. As discussed earlier the date pattern for failure is not specific so we extent it into full calendar year specifying the date of failure. But there arises a problem of mismatch for prediction, the number of failures days is very less as compared to the non-failure dates otherwise the prediction will be less accurate. So we create a special technique by which the data taken into consideration becomes considerably equal in both conditions. The parameters upon which the performance of the neural network created are precision, F^1-score and recall. Precision is measure that is the proportion of true positives to the amount of total positives predicted by the model. Recall focusses on the performance of the model in finding all the positives. F^1-score is a trade-off between precision and recall and how effectively that trade-off happens.

$$Precsion = \frac{TP}{TP + FP} \quad (1)$$

$$Recall = \frac{TP}{TP + FN} \quad (2)$$

$$F1\ Score = 2 * \frac{Precision * Recall}{Precision + Recall} \quad (3)$$

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (4)$$

The type of failure and time to failure does not depend upon the date of activity or the type of activity conducted during the testing phase. Also since the occurrence of failure is not linear it does not follow a definite pattern. Thus prediction of a definite type of failure cannot be attained by considering the results as a whole. Instead each type of failure has to be segregated and then the date of occurrence of each failure separately is used to forecast the next date of occurrence according to the time interval specified. For this feature engineering is done on the dates given so as to get a detailed or parametric estimate the specified date precisely.

After the feature engineering part is done then the data is split into train and test data. The size of train

data is selected accordingly is 70% of the total data since that is found to be the most efficient way. Then by using ANN architecture a suitable model is designed for forecasting the data.

VIII. RESULTS

The only parameter provided was the frequency of fault occurrence, as known does not follow any specific pattern. Feature engineering done in case of the date of fault occurrence has given the neural network more values to work on, therefore getting more accurate results. The presented case covers a rather limited system and it is easy to see the complete picture. All the failures are listed and then assessed one at a time. In this project development different assumptions were considered such as only one test is conducted each day and also if more than two failures occur on the same date the first failure is taken into consideration.

From the given set of information which contains the type of test conducted, the date on which failure occurred, the type of failure occurred and the time to failure are all given for ten consecutive years, the main idea is to forecast the type of failure, probable date of failure and the time to failure from the present date to the required time interval. From this data the number of each failure that is going to occur in the given time interval. By using a proper training set extracted from the given data the prediction model is created and the designed model is verified by test set. Upon verification the confusion matrix is created.

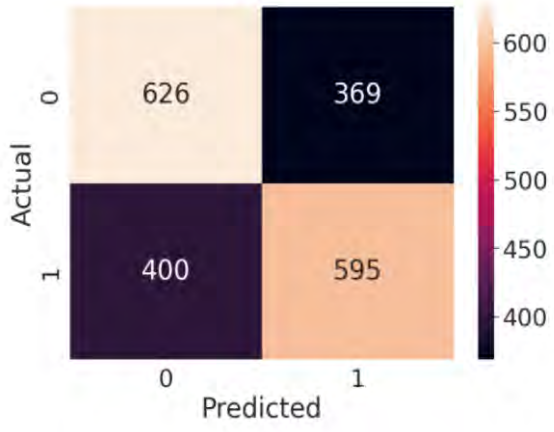

Fig 4: Confusion Matrix of Hardware Failure

The confusion matrices for hardware failure, hardware triggered software failure are provided by Fig.[4] and the confusion matrices for software failure and software triggered hardware failure is given by Fig.[5]. From the confusion matrices we obtain the parameters mentioned in section VI.

Altogether the precision, recall, F1-score and accuracy are 62%, 64%, 63.5% and 63% respectively.

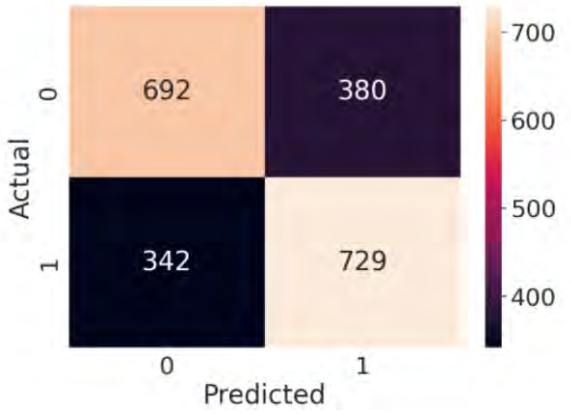

Fig 5: Confusion Matrix of Hardware Triggered Software Failure.

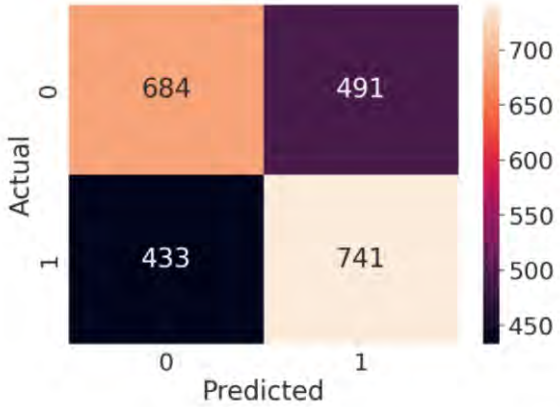

Fig 6: Confusion Matrix of Software Failure

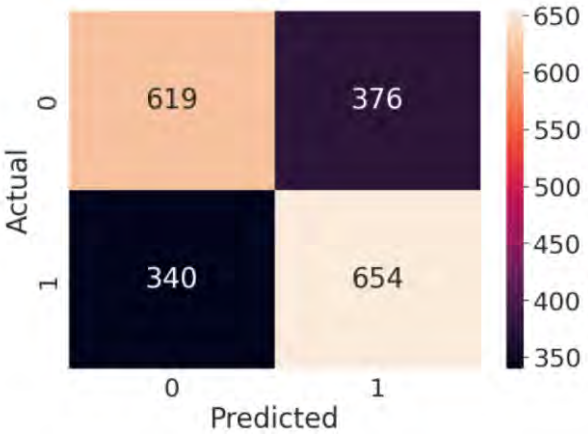

Fig 6: Confusion Matrix of Software Failure

From Fig.7 the expected number of failures diversified as predicted by ANN is depicted.

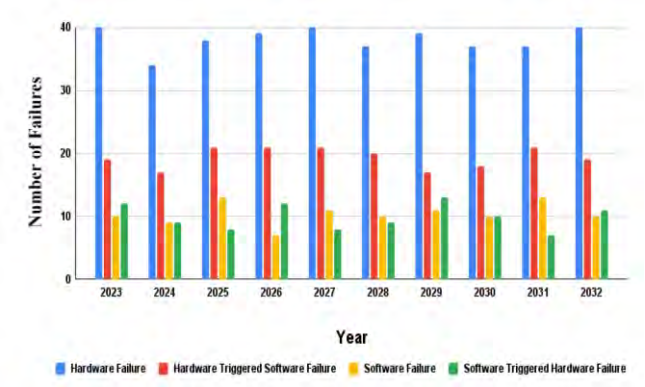

Fig 8: Number of Failures Forecasted From 2023 to 2032.

The cumulative time to failure is calculated by using prophet forecasting technique. Feature engineering was used for converting the failure dates available for creating the model for forecasting the next failure incident and next type of failure slightly to occur. The next instant at which that type of failure might occur if the test run is done on the platform comparing to the previous day is given in Fig. 7 and Fig. 8 respectively

As can be observed from the results as time passes the number of hardware failure tends to increase in number because of some slight damage in the hardware components.

TABLE II. Prediction of Next Time to Failure

S. No.	Next Time To Failure (hrs)	Type of Failure
1	5	Hardware Failure
2	11	Software Failure
3	14	Hardware Failure
4	21	Software Failure
5	33	Hardware Triggered Software Failure
6	49	Hardware Failure
7	122	Software Triggered Hardware Failure
8	155	Hardware Failure
9	194	Hardware Triggered Software Failure
10	205	Software Failure

Whereas the number of software failures decreases comparatively. Most of the correlated failures have reduced in number as time passes the rectification process will be done. From table II the time at which the platform failure might happen after working for the prescribed time interval is observed.

IX. DISCUSSION

Using the data available, following were intended to be predicted using DL techniques.

a. Time of next anticipated failure (In calendar data or Execution time)
b. Type of next anticipated failure (Hardware Failure, Software Failure, Hardware Triggered Software Failure or Software Triggered Hardware Failure)

The methodology proposed here would aid in generating the above two important aspects/ parameters of influence of maintainability. When these critical data are available, for any specific electronic equipment, it would be easier for the ground support team to get prepared with required Ground Support Equipment / Ground Handling Equipment. In addition, a suitable inventory or team could also be made available, for certain type of failure postulated/anticipated using DL. It could be appreciated that, when these postulation/predations are accurate, inventory management could be optimized to the lowest, thereby reducing LCC.

X. CONCLUSION

Although RCM is widely adopted to eliminate potential failure modes from the field, it does not provide any quantified outcome, upon implementation. Using conventional methods, both RCM & ACM along with MSG-3, aim to shorten / optimize maintenance tasks. However, these approaches do not provide insights into the health of the system or assure fault free duration of operation or what kind of maintenance actions are to be initiated at what point in time. We have attempted to provide clarity on each of the points discussed. The approach proposed here would determine anticipated type of failure for an electronic equipment along with expected type of

failure. Using these data, the down time of the platform could be drastically reduced, especially in the case of unscheduled maintenance, which is often triggered by electronic equipment on the platform.

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Time Series Data Compression using Piecewise Linear Model for Aircraft Health Monitoring Applications

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Abstract - Any modern civil or fighter aircraft will monitor the aircraft by thorough verification of all major system functionalities using the sensors installed at identified locations. The sensor data acquired during every flight will be used for onboard real time monitoring and this data will be recorded in Flight Data Recorder (FDR) for off line analysis to verify the health status of the systems.

The data generated from all systems will be huge, hundreds of Mega Bytes and hence data management becomes difficult as the data size grows with every flight activity. Standard data compressions techniques will not provide efficient solutions due to the nature of data and presence of multiple type of data files. Hence the use of the advanced data compression techniques to minimize the data storage requirements are being explored.

Piecewise Linear Model (PLM) is such novel, simple and low complex univariant technique developed for the compression of temporal correlated data. This method yields high compression without losing valuable information after reconstruction. Using the PLM concepts, the data compressions carried out shown the significant results without losing the information and with consistent data accuracy. The details of studies carried out for data compressions using PLM and other methods are presented in this paper.

Keywords - component, formatting, style, styling, insert, compression, reconstruction

I. INTRODUCTION

Any aircraft based on their purpose of usage, acquire flight parameters system specific sensors data like vibration, pressure, temperature, strain gauges and recording of audio and video files. The sensors data generated from military aircraft is generally non-linear and non- stationary due to the various maneuvers, which are dynamic in nature. The sensors data is generally in digital or analog format represented as data ascii files, need be processed and retained for many years or lifetime, to track the history of aircraft systems. In this paper, studies are focused on this ascii data files and their compressions.

Among many methods reported in an open literature for compressing the aircraft data, few methods are discussed here for highlighting associated key aspects. Sparse PCA [1] is the technique used to compress the data by exploiting the spatial correlation among the various independent variables. High compression is achieved if the dependent variable has the good correlation with the input parameters. Delta encoding [2] is another method, which considers the difference between the successive data points instead of storing the absolute values. It is effective when the difference between the adjacent data points is small. Compression using Moving average method [3] calculates the average of a fixed-size window of data points and stores only the average values. This reduces the amount of the data stored while capturing the general trend. Singular Value Decomposition (SVD) [4] can be used to decompose the time series matrix into three separate matrices, representing the signal, temporal patterns, and noise. By discarding components with small singular values, the data can be compressed. Piecewise Linear Model (PLM) considers the training of dataset for deriving the model parameters and is the best suitable for

spatial-temporally correlated data to achieves high compression. PLM model is a common well-known technique but the novelty lies in the specific adaptations, improvements and innovation introduced to compress the temporal data.

II. COMPRESSION TECHNIQUES

A. Linear Segmentation

Linear segmentation is the data analysis technique that involves dividing a dataset into the segments or intervals, and within each segment, fitting the linear model to describe the relationship between variables. The linear segmentation approach is particularly useful when dealing with the dataset that exhibits different line trends in different region of the dataset, as it follows more accurate representation of the underlying relationships.

Liner segmentation begins with the process of segmenting the dataset into distinct intervals. The segmentation goal is to identify regions where relationship between the variables appears to be the linear.

B. Real time data compression technique.

Real time data compression is the process of reducing size of data while it is acquired by the data acquisition system in real-time. This compression technique aims to efficiently store the data by eliminating the unwanted data points or data points which are falling within the allowable limit. Real time data compression is particularly valuable in scenarios where data needs to be processed on ground, reduce the storage requirements on board and improve the overall transmission efficiency with low latency. The latency of a PLM compression technique in real time application depends on several factors like hardware and processor memory, segmentation complexity and dynamic training time of the PLM model.

C. Offline data compression technique.

Offline data compression is the technique used to reduce the size of the data files by storing the limited data points using the lossy and lossless data compression methods [5]. Unlike real-time compression which occurs while acquiring the data, offline compression takes place after the completion of sortie. Offline compression is essential to save storage space and optimize the data management.

D. Lossy and Lossless compression

Lossy Compression: PLM compression is a lossy data compression technique used to reduce the size of the data by intelligently discarding some of the information within the allowable limit in a way to achieve the high compression ratio. The allowable error limit shall be determined by the domain experts to avoid the significant loss of information. With any lossy compression technique, there is a trade-off between data reduction and loss of information. Depending on the techniques and algorithms being developed, some details in the data can be lost to achieve the compression.

Lossless compression: is the data compression technique that reduces the size of the data without losing any information. Unlike lossy compression, which sacrifices some details to achieves the higher compression ratios, Lossless compression ensures that the original data can be perfectly reconstructed from the compressed data. The compression using the .zip and 7z formats are popular file compression techniques uses different compression algorithms. As the lossless compression algorithms works on the entire dataset and files, it may not be applicable to use in real time for compression.

III. PLM METHOD

A. PLM Compression Principle

In a Piecewise Liner Model (PLM) [6] system, the dataset undergoes segmentation into multiple linear segments to capture the data variations and nonlinear relationship. The PLM model is then trained on this segmented dataset to derive its model parameters. Then the trained model is employed for making the measurement predictions. In this process, if the squared error exceeds the given prediction error tolerance, the model weights are retrained. This approach

ensures that the error tolerance consistently remains within the acceptable limit. The compression achieved through this method involves by storing only the end data points of the linear segments instead of storing all the measurements.

Sensor's measurement is represented in the Fig.1. The dataset is divided into linear segments using the break points and then each linear segments are independently fit using PLM model.

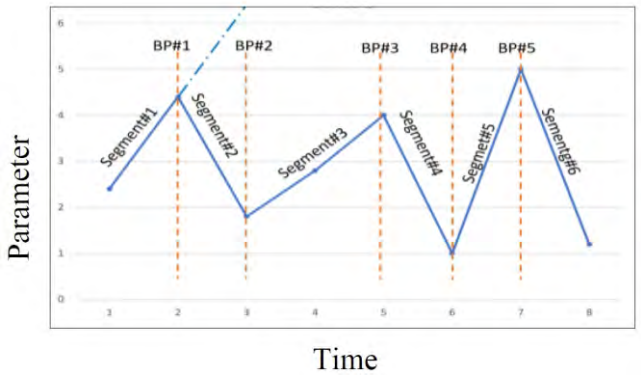

Fig.1 Break points and linear segments of a signal.

Let us consider the measured dataset as,

$$Z = \{X_1, X_2, \dots, X_n\} \quad (1)$$

Where each data point is defined as,

$$Z = \{(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)\} \quad (2)$$

PLM model considers the initial two measurements (X_1,Y_1) and (X_2,Y_2) of linear segments for computing the coefficients (W_1,W_2)

$$Y(i) = w_1 + w_2 * x(i) \quad (3)$$
$$Where\ i = 0,1,2, \dots, n$$

B. PLM System Model:

Y represents the predicted vector of the measurements. The squared error is calculated with reference to every predicted data points. If the error surpasses the acceptable error tolerance, the model parameters will be recalculated.

Squared error is the square of the difference between the predicted value and actual measurement. This parameter is computed at every time instant to verify and control the error tolerance against allowable limit.

$$\text{Squared error } \in = (\hat{y}_i - y_i)^2 \quad (4)$$
$$Where\ i = 0,1,2, \dots, n$$

Non-linear data will be segmented into linear segments at the breakpoints. These breakpoints will be dynamically defined at the time instant when the squared error exceeds the allowable error tolerance.

$$BreakPoint(Tbp) = T, \quad (5)$$
$$where \in > Threshold$$

C. Performance measurements

The performance of the method shall be assessed based on the compression of data achieved and accuracy of the results.

a. Compression Ratio

The compression ratio quantifies the level of compression achieved for a given dataset, and the compression ratio determined through the following computation,

$$\xi = \frac{m}{n} * 100 \quad (6)$$

Where m- is the total number of compressed data points and n-is the total number of measurement points.

b. Normalized MSE (NMSE):

Normalized mean squared error (NMSE) is a statistical metric used to evaluate the performance of the model and provide the relative measure of the error to interpret and compare across the dataset. Normalized MSE is computed as follows,

$$NMSE = \frac{MSE}{MSV} * 100 \quad (7)$$

Where MSE is the Mean of squared Error and MSV is the Mean of Squared Value.

NMSE value 0% indicates the data prediction without any error, and the value 100% indicates the complete error in the data prediction.

c. Threshold selection and tradeoff optimization

Selecting the threshold for the given individual parameter plays the pivot role in the PLM compression technique. The parametric threshold depends on the trade-off between the compression ratio and MSE incurred. The maximum MSE can be allowed shall be lower than the allowable error tolerance for the parameter. Higher the threshold will lead to higher compression ratio and incurs the higher MSE. Threshold value shall be selected by studying the trade-off between the MSE and Compression ratio.

D. PLM technique applicability in real time applications

PLM compression techniques can be applied in various dataset where data compression, approximation of complex datasets is required while preserving the essential information. Following are some applications:

a. Data compression in IoT and sensors network:

In internet of Things (IoT) and sensors networks, data transmission and storage can be resource-intensive. PLM can be used to compress the sensors data by approximating the sensors readings with piecewise linear functions. This reduces the amount of data that needs to be transmitted and stored while maintaining accuracy for certain applications.

b. Data reduction in Time-Series Analysis:

Time -series data often contains noisy or redundant information. PLM model can simplify time-series data by approximating trends and detecting the anomalies [7] in data with linear segments and reducing the storage requirements.

c. Curve Fitting:

In scientific and engineering applications, PLM can be used for curve fitting when the underlying data does not follow a continuous curve.

Piecewise linear model compression allows for a balance between data reduction and preserving essential information in various domains. Its effectiveness depends on the specific characteristics of the data and the requirements of the applications. The PLM technique outperforms the some of traditional dimensionality [8] reduction and machine learning methods to achieve the higher compression.

E. PLM compression algorithms

A concise description of compression methodology is presented in the algorithm. Sensor's data and threshold is given as input to the a $S \in R^{nx2}$ For every time instant we predict the value and compute the squared error with reference to the original value. We only store the initial and end data points of the linear segments to achieve the compression. Model parameters are recalculated and updated in the model equations if error exceeds the given threshold value , as shown in Table 1. This process continues $\epsilon > \gamma$ we acquire data from the sensors.

F. PLM reconstruction algorithm

Algorithm1: PLM Compression Algorithm

Output result: Compressed data: z ∈Rm

Input data: FDR data: $S \in R^{nx2}$;
Initialization: $i = 0;\ \gamma = 0.1;$

Initial sample set: $So \in R^{2x2}$;
Compute the model parameters: $\{w_0,\ w_1\} =$ $plm\_model\ (x[0:2];\ y[0:2]);$
Append initial datapoint of segment: $Z = \{x_0, y_0\}$
for data_range *do:*
  Prediction: $y\_pred\ =\ plm(x[i])$
  Compute squared error: $\varepsilon\ =\ (y_i - y_{pred})^2$
  If $(\epsilon > \gamma)$ **then**
    Recompute the coefficient with new set of data points
    $\{w_0, w_1\} = plm\_model\ (x[0:2];\ y[0:2]);$
    Append initial datapoint of segment: $Z =$ $\{x_i, y_i\}$
    $i = i + 1$
  end
end

PLM reconstruction algorithms working process is described in the algorithm.2. The algorithm uses the PLM reconstruction model to predict the actual data points. The compressed data will be provided as input to the PLM reconstruction model to generate the original data.

G. Other Compression Methodology and their comparision

Algorithm2: PLM reconstruction algorithm

```
Output result: Reconstructed data : y_rec ∈ R^n
Input data: Compressed data : y_comp ∈ R^(nx2);
Initialization: i = 0;
  for comp_data_range do:
    Prediction: y_rec = plm_rec_model(x[i])
end
```

a. Piecewise polynomial model

Piecewise polynomial model is a mathematical technique used to approximate a nonlinear function or dataset by breaking it down into smaller segments and representing each segment with a separate polynomial equation. Instead of using single polynomial to describe an entire dataset, piecewise polynomial models use different polynomial functions for different intervals of the data.

Polynomial fitting within each segment, a polynomial model is chosen to approximate the data. The degree of the polynomial function is chosen to fit each segment of the dataset. The selection of the polynomial degree plays an important role with reference to the data compression.

The compression achievement using higher degree polynomial model will be lower as it requires to store more data for the accurately reconstruct the data.

b. Peak and valley (PV) compression methods

Peak and valley (PV) algorithms will determine the PV data points based on the slope change in the data streams. The compression using PV algorithms will be achieved by storing only the peak and valley datapoints with respective time instances, which is required for decompressing data. Compression obtained of this method highly depends on the nature of data. For non-stationary and highly dynamic data, the compressibility will be significantly low.

Mean Squared Error (MSE) incurred in this method will be zero or negligible. PV compression algorithms do not require any error tolerance for the compression. This real time compression method can be applied where error tolerance is not allowed and compression achievement is not the main criteria.

IV. RESULTS AND DISCUSSIONS

Piecewise linear model aims at high compression ratio for both linear and non-linear data. Compression is achieved by exploiting the spatio-temporal correlation in the given dataset. In this method, MSE will be highly controllable and will not exceeds the given error tolerance. PLM is a simple technique developed for the real time data processing applications and data compression requirement will play a key role in minimizing the data points for quick analysis. This method can be applied in the aircraft data management and utilize the onboard memory space effectively.

A. Compression results across various dataset

a. The triangular signal

The simulated triangular signal with single breakpoint is used for the compression to understand and explain the working principle of the PLM technique. Fig.2a shows the original signal data while Fig.2b represents the reconstructed data plotted against the original signal.

The PLM model breaks data into two linear

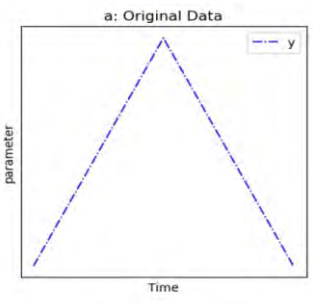

Fig.2a. Original data

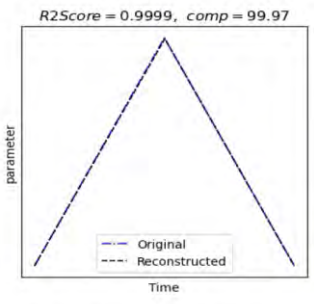

Fig.2b. Reconstructed data mapped on to the orginal signal

segments and models each segment with appropriate parameters. The PLM model stores only the endpoints of each segment

Triangular signal with 20000 data points is compressed to the size of 6 data points. Achieved compression percentage is 99.97 with MSE value 0.0183 which is within the allowable limit.

Table.1. Triangular signal compression results:

Data	Triangle Wave
Original data size	20000
Compressed data size	6
Compressed percentage	99.97
R^2	99.99
NMSE (%)	0.002

b. Continous wave signal

The continuous wave signal generated using multiple triangles signals shown in Fig 3a is used as a test case for PLM compression. This data is provided to the PLM model for the compression, with threshold value 0.1. The compression of 99.92% is achieved with the MSE value of 0.852. Fig.3b represents the reconstructed signal plotted on to the original signal for their comparison.

The continuous wave signal with 100000 data points is supplied for the PLM compression and the data size was reduced to 80 points which is 99.92%. The incurred MSE value is 0.04359 which within the allowable limit.

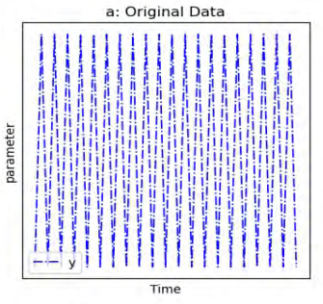

Fig.3a. Original data

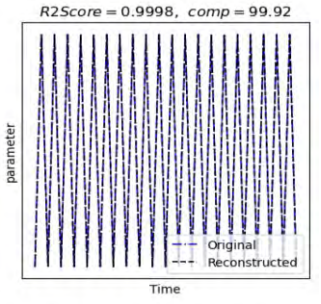

Fig.3b. Reconstructed data mapped on to the orginal signal

Table.2. Continuous wave signal compression

Signal	Contineous Signal
Original data size	100000
Compressed data size	80
Compressed percentage	99.92
R^2	99.98
NMSE (%)	0.005

c. Realtime aircraft dataset

PLM compression technique performance was tested on the real time aircraft dataset. Pressure altitude of aircraft data recorded during the flight was considered for this study. Using this method, the compression was achieved is 97.14% with accuracy about 99 % and above. The comparison plot of actual and reconstructed data with details are shown in Fig 4a and Fig4b.

a) Pressure altitude by PLM

b) Inflight measured strain data

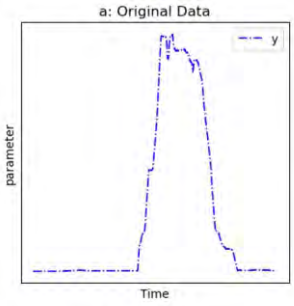

Fig.4a. Original data

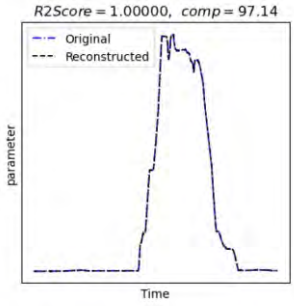

Fig.4b. Reconstructed data mapped on to the orginal signal

Table.3. Pressure altitude Compression

Compression Technique	PLM	PPM	PV
Original data size	203370	203370	203370
Compressed data size	5820	18724	16228
Compressed percentage	97.14	90.79	92.02
R^2	99.99	98.99	97.81
NMSE (%)	7.9e-6	3.07e-6	0.0825

Inflight measured strain gage data was considered to test the compression as one more test case to study the performance of this method. Against number of points about 2.7 Lakhs, algorithm reduced them to points below 10000 with accuracy R^2 above 99.5%, as shown in Fig 5a and 5b respectively.

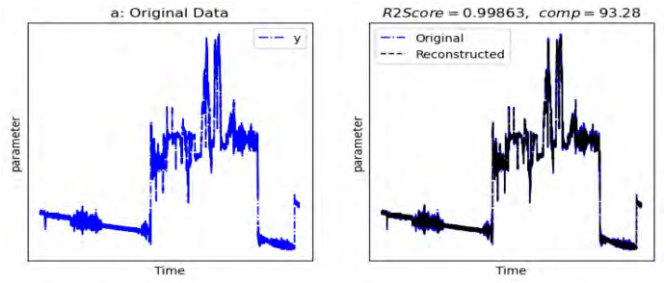

Fig.5a. Original data

Fig.5b. Reconstructed data mapped on to the orginal signal

Table.4 Measured strain data compression

Data	PLM	PPM	PV
Original data size	267508	267508	267508
Compressed data size	17964	24000	30000
Compressed percentage	0.93	0.91	0.89
R^2	99.86	98.90	97.46
NMSE (%)	0.118	0.120	0.138

V. CONCLUSION

PLM compression methodology was developed and tested for aircraft dataset such as presure altitude, Mach number and , strain data. It was observed that this method holds good with compression above 90% depending on the nature of the data and allowable threshold limit. This methodology can be best utilized in real-time compression as well as the off line data compression for effective utilization of storage memory.The peroformance of PLM compression technique, PPM and peak-valley methods are tabulated in table.3 and table.4 and it was observed that performance of PLM is superior when compared to the other methods.

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Development of a Data Analytics Tool for Flight Strain Predictions

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Abstract - Ensuring the availability of an aircraft is critical for accomplishing missions and achieving commercial objectives. Therefore, all aircraft industries employ health monitoring techniques to verify the system's condition and plan maintenance accordingly. Diagnostic and prognostic algorithms, developed under Health and Usage Monitoring Systems (HUMS) or Integrated Vehicle Health Management (IVHM), play a vital role in assessing the health condition or state of aircraft systems. Typically, these algorithms are implemented using ground-based software tools that process the recorded flight data.

When developing algorithms centered on data analysis, correlations and predictions play pivotal roles. Validating these algorithms and assessing the suitability of methods for analysis before considering their integration requires a dedicated platform.

This paper introduces the creation of a software tool designed to forecast system parameters like strains, pressures, vibrations, etc., utilizing flight parameters. The tool automates testing across diverse regression models by employing different combinations of flight parameters and system sensor data. Constructed on Django, a Python framework, the tool integrates multiple data analysis methods including correlation, regression, statistical summaries, and data visualization techniques. In this paper, the concept is demonstrated using data comprising of strain gauges and flight parameters for monitoring the health of an airframe structure.

Keywords - Data analytics, Django, flight parameters, flight strains, aircraft health

I. INTRODUCTION

Data analytics has gained significant importance in the aircraft industry, as it explores diverse methodologies to make accurate predictions for various applications[1][2]. Both civil and military aircrafts collect data during flight and perform onboard processing to execute specific functions. In-depth real-time or offline analysis of this flight data, consisting of common flight parameters (e.g., normal acceleration, altitude, speed, etc,.) and system-specific sensors' data, is then conducted to verify system performance[3].

A critical aspect of aircraft system analysis is health monitoring, which involves assessing the system's

condition and planning necessary maintenance actions for improving aircraft availability. This process necessitates the development of mathematical models that predict the behavior of specific parameters and analyze previously acquired data to evaluate health status. To facilitate this analysis, mathematical tools such as MATLAB and Python are commonly employed to develop various data analysis techniques such as regression, Support Vector Machine (SVM), Random Forest (RF) and Artificial Neural Network (ANN). The aircraft industry frequently utilizes software tools to simplify the execution of such analyses, particularly in developing diagnostic and prognostic algorithms as part of Integrated Aircraft /Vehicle Health Management (IVHM) technologies.

Vast amounts of data are generated during aircraft operations, and there is an emphasis on the analysis of this data worldwide. The purpose of this analysis is to determine the health condition of aircraft systems, enabling proactive maintenance planning for optimal aircraft operation. In today's world, the development of algorithms rooted in data analytics plays a pivotal role in this process. It is important to validate these algorithms and assess the suitability of various methods before deciding on the integration of a specific algorithm. This necessitates the availability of a robust tool for checking and validating the developed algorithms.

In the field of data analytics, researchers employ various methods, including supervised and unsupervised techniques, conventional gradient-based or random-based approaches, etc. The effectiveness of these data analysis algorithms is heavily reliant on the data.

Aircraft data is generally structured and familiar, making it eligible for supervised machine learning. The effectiveness of data analytics methods in making accurate predictions relies heavily on the extraction and utilization of key data features. The foundational step in this process involves building prediction models using historical data features, often referred to as training models.

A data analyst must thoroughly examine the data, forecasting methods, and resultant outcomes to determine the appropriate next steps. This includes assessing the suitability of methods, ensuring effective representation and extraction of features in the data analysis, and understanding the results before implementing them on site. To facilitate this, a robust tool that seamlessly integrates the methods developed, provides a clear display of results, and enables in-depth examination of all aspects within a unified framework.

This paper presents the development of such a software tool for making predictions of key system parameters such as strains, pressures, vibrations, etc., using the acquired data such as flight parameters and specific system sensor data. The tool is built using Django, a Python framework.

Python language is widely used in the realm of data science due to its rich libraries. This tool makes use of libraries like pandas [4], NumPy [5], Matplotlib [6], Seaborn [7], and sklearn [8], which simplify data analytics. Django [9] is an open-source Python web framework. It streamlines web development by providing useful libraries for tasks like authentication. It seamlessly integrates Python, HTML/CSS[10] and various database systems, making app creation easier. PostgreSQL[11], the chosen database system, excels in securely storing and scaling complex data workloads, supporting various data types, indexing methods, and data integrity mechanisms. Hence, this tool harnesses the powerful combination of Python, Django, and PostgreSQL to achieve its objectives effectively.

II. ANALYSIS

Flight parameters are specific variables that define the state of an aircraft during its operation. Some common flight parameters include normal acceleration, pitch rate, fuel remaining, aircraft mass, weight on wheels, etc. In addition to these common parameters, system specific parameters are also used for monitoring the system's performance and usage.

Strain gauges are strategically positioned on an

aircraft's airframe structures to measure mechanical strain under different loads. The data derived from these gauges is crucial for monitoring the aircraft structure's health and estimating the fatigue life of its components. Structural Health Monitoring (SHM) studies commonly involve analyzing flight parameters alongside strain gauge data to evaluate responses during various events.

Present work contains two areas as listed below.

1. Data analytics for strain prediction using flight parameters
2. Tool development

2.1 Data analytics for strain prediction using flight parameters

In the present study, flight parameter data has been utilized to predict strain using machine learning techniques. Models have been developed by utilizing historical flight parameters data, which can be created through regression analysis, artificial neural networks (ANN) and other machine learning algorithms. These models are crucial for predicting strain profiles and subsequently verifying them against measured values, playing a pivotal role in Structural Health Monitoring (SHM). The tool discussed in this paper serves this very purpose.

Some algorithms that were explored to build the models were regression techniques like linear regression, multilinear regression, ridge/lasso regression, decision tree regression, random forest regression, etc. Machine learning algorithms like artificial neural networks (ANN), K-Nearest Neighbors Algorithm (KNN), Support Vector Regression (SVR), and boosting algorithms like AdaBoost, XGBoost, CatBoost and gradient boost can also be used to achieve the same. These models can readily be incorporated into the tool and compared to find the most suitable algorithm.

To develop the regression model, the flight parameters and strain gauges data were interpolated to a common sampling frequency. Correlation studies were conducted for each strain gauge. Flight parameters showing high correlation with specific strain gauges were selected to train the regression models. Additionally, principal component analysis can be employed for dimensionality reduction. Each strain gauge data was split into training and testing sets. The model was developed using the training set and verified using the testing set. Various regression techniques, including linear regression, multilinear regression, and ridge regression, were applied to actual flight sortie data, and integrated into the tool [12],[13].

The results obtained from these regressions yield valuable insights and can be used for the following purposes:

- Detecting anomalies
- Identifying unhealthy signatures or patterns
- Estimating fatigue life using strain signatures, even in cases where measured strain data is unavailable.

The contributions by various flight parameters to a strain gauge value can be represented through a heat map as shown in Fig. 1. Higher the coefficient, better the correlation with strain.

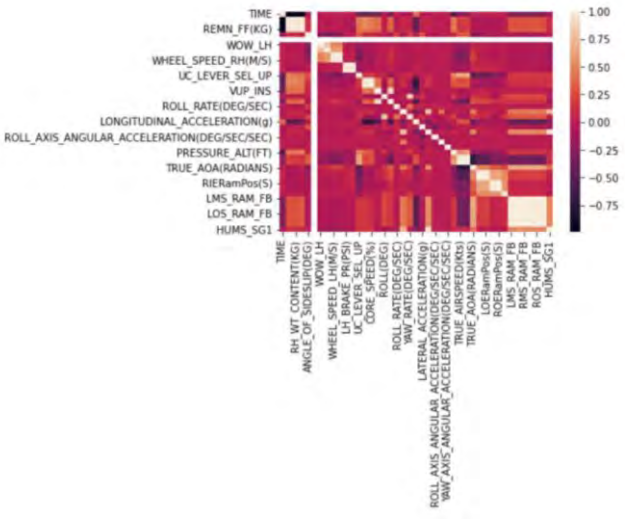

Fig 1. Heatmap for strain gauge 1

Figures 2, 3, 4 and 5 show some examples of the regression analysis performed along with the regression scores for those methods. The R2 (R-squared) score is the proportion of variation of the dependent variable that can be explained by the independent variable(s).

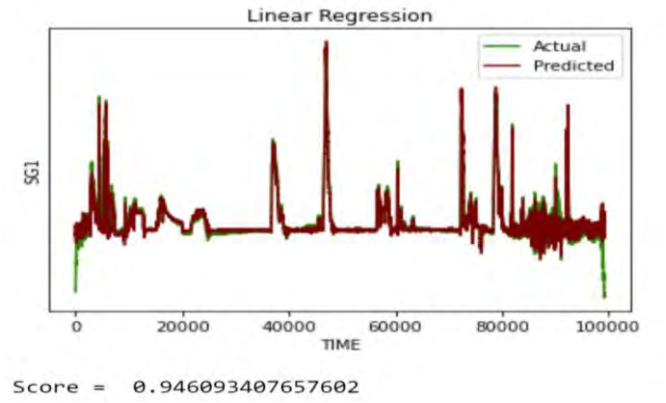

Fig. 2. Result of linear regression for strain gauge 1 (independent variable: normal acceleration)

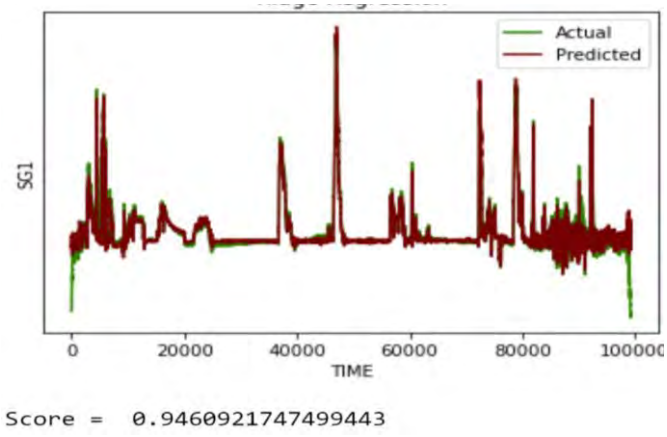

Fig. 3. Result of ridge regression for strain gauge 1 (independent variable: normal acceleration)

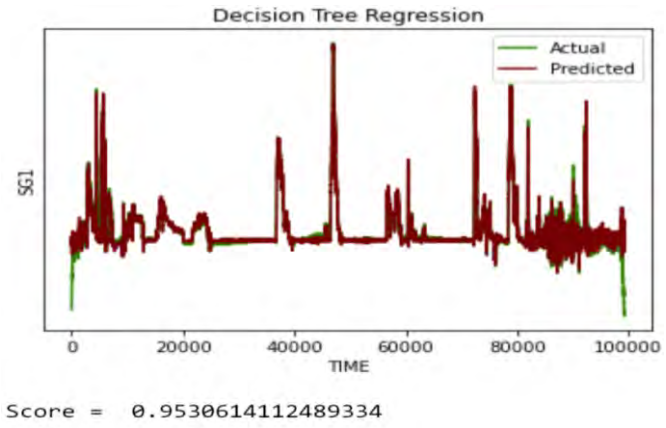

Fig. 4. Result of decision tree regression for strain gauge 1 (independent variable: normal acceleration)

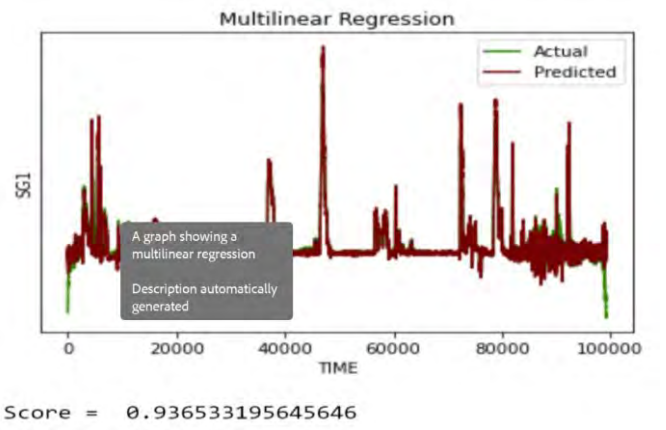

Fig. 5. Result of multilinear regression for strain gauge 1 (independent variables: normal acceleration and pitch rate)

The R^2 scores that were obtained in each method shown in the respective figures are listed below for better readability and comparison.

Linear regression	94.61%
Ridge regressions	94.61%
Decision tree regression	95.31%
Multi linear regression	93.65%

This metric indicates the extent to which the predictions generated by the model align with the actual signature. If this value consistently remains above a specified threshold, such as 90%, it suggests that the signature aligns with normal behavior and the health condition is deemed good. However, if the score falls below, for example, 75%, it signifies a lack of synchronization between the actual data and the model's output. This situation warrants further analysis for anomaly detection or identification of system degradation.

A few methods have been integrated into the tool for processing the data and storing the required processed information in the database. New methodologies or algorithms can easily be integrated into this platform. All integrated algorithms are readily executable. The user can choose a few, or all the methods available and compare the results for the same input files. Evaluation metrics suitable to each algorithm can be employed to gauge the models' performance effectively.

2.2 Tool Development

The tool has been integrated with the machine learning methods developed for the analysis of strain gauge data, as well as a few visualization techniques. The architecture of the tool is as shown in Fig. 6.

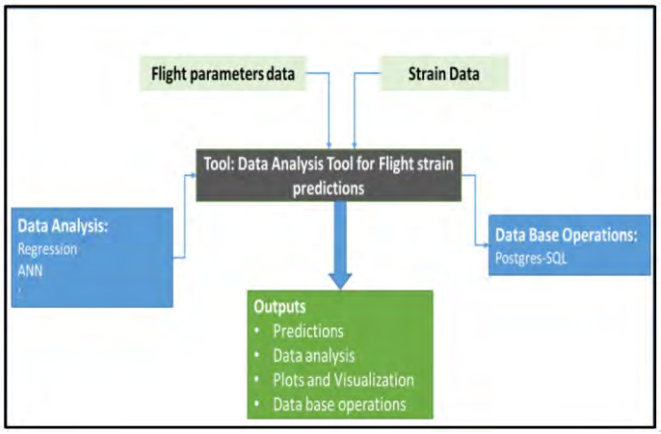

Fig. 6. Architecture of the tool

So far, the tool has successfully implemented authentication, database connectivity [14], some data visualization techniques, and a variety of regression methods. Given that our primary objective is to build a regression model, the tool is designed to store the results of the regressions performed in the database for easy access. The following few figures give a basic idea of the tool's functionalities.

Fig. 7 showcases the tool's login page.

Fig. 7. Login functionality

Fig. 8 corresponds to the visualization facility. The user is required to choose the desired files, select a strain gauge, and flight parameter(s). The plots generated are – signatures of the strain gauge and the chosen flight parameter(s), graphs of the strain gauge vs. the flight parameters.

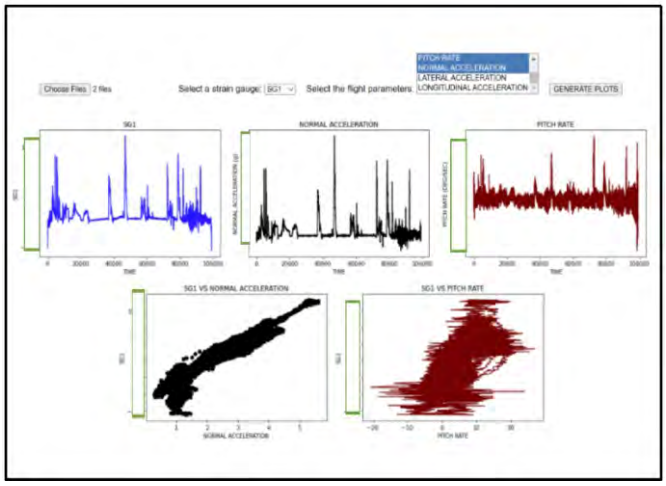

Fig. 8. Visualization page

Fig. 9 gives an example of the tool's regression functionality. The user can pick a strain gauge, flight parameter(s), and the desired method of analysis from the drop-down, eg: linear regression. Once the 'Go' button is clicked, the tool will perform the analysis and present the results accordingly. The result contains the regression score as well as a graph with the actual and predicted strain values.

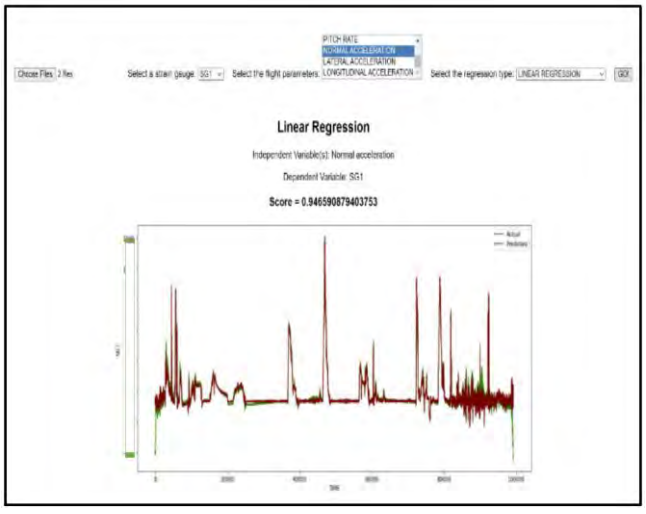

Fig. 9. Regression facility

Fig. 10 is how the database view saves and displays the data of the regressions performed by a user.

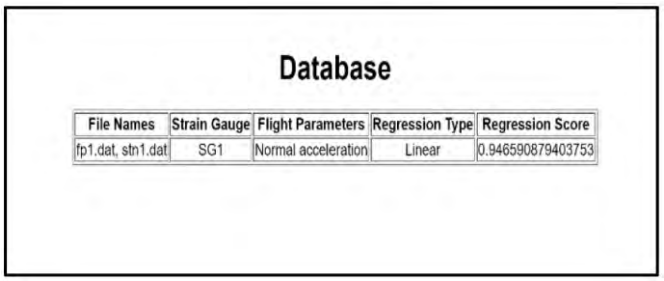

Fig. 10. Database view

To further enhance the tool's capabilities, it can be extended to incorporate additional regression methods, allowing users to compare and evaluate different regression techniques for their specific applications. A facility for K-Fold cross-validation can also be added to see if the model in question can generalize well.

IV. CONCLUSIONS

In this paper, we presented the development of a software tool, using Django, a Python web framework incorporating various data analysis methods, such as correlation, regression, statistical summaries, and data visualization techniques. The tool was built for predicting system parameters and analyzing the health of aircraft systems using flight data.

The tool's application extends beyond the specific use case presented in this paper. It can be adapted and expanded for other aircraft systems and health monitoring applications, making it an asset for the aviation industry.

In conclusion, the development of this software tool represents a significant step towards enhancing aircraft health monitoring capabilities and contributing to the overall safety and reliability of aviation operations. With further advancements and refinements, such tools are poised to play an increasingly pivotal role in the future of aircraft maintenance and performance optimization

V. ACKNOWLEDGEMENTS

We would like to extend our gratitude to Aeronautical Development Agency and PES University for their support.

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Digital Framework for Indigenous Fighter Aircraft Development & Sustenance

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Abstract - The Military has been looking for sustainable fighter aircraft with improved mission performance and operational availability at reduced lifecycle costs. Against the backdrop of induction of the Tejas into the Indian Air Force, the design and development community is gearing up to meet the demand by adopting advanced manufacturing technologies, improved product support strategies and integrated logistics while reducing the development cycle time of new products.

Similar to developing an airworthy product, developing a sustainable product too is a multi-disciplinary activity which needs a collaborative and connected digital framework spread across the enterprise. Early adoption of such an ecosystem enables continuous improvement in availability of aircraft while ensuring superior product support during sustainment. This paper discusses how a Service Lifecycle Management system interfaced with other existing enterprise systems would help establishing a consortium of digital systems to facilitate digital thread throughout the product lifecycle (end-to-end) while maintaining 'single truth' all the time.

Keywords - Sustainability, Availability, Service Lifecycle Management, Connected Digital Framework, Digital Twin, Digital Thread

I. INTRODUCTION

Under the Atmanirbhar Bharat Abhiyan, India is continuously growing in its power to indigenously design, develop and manufacture advanced weapon platforms to the military. The Cabinet has approved procurement of 83 Tejas fighters for the Indian Air Force. This is the largest indigenous defence procurement deal worth Rs. 45,696 Crore [1]. In 2022, the Cabinet Committee on Security (CCS) has sanctioned the project to design and develop Tejas Mk 2 fighter [2] which is likely to begin flight testing in two to three years. The process for obtaining CCS approval for developing Advanced Medium Combat Aircraft has been initiated [3]. The Indian Navy along with ADA/DRDO are proactively pursuing design and development of an indigenous Twin Engine Deck Based Fighter [4]. The draft policy on Defence Production and Export Promotion aims to achieve an export of Rs. 35,000 Crore (US$ 5 Bn) in aerospace and defence by 2025 [5]. The defence organisations plan to work in tandem with private industries while adopting modern strategies and tools like Industry 4.0, Digital Thread, IoT, Block-Chain and Artificial Intelligence [5] to realise sustainable products.

The Staff Requirements of these programmes have emphasised more on sustainability and availability of fleets. Sustainability draws this attention due to the long lifecycles of military aircraft (> 40 years). The operating and support

costs of military aircraft make up to about 65-80 % of its lifecycle costs as shown in Fig. 1 [6]. The long lifecycles emanate additional challenges for the Development Agency/OEM to cater for life extension, upgrades and technology insertion as per changing warfighting requirements.

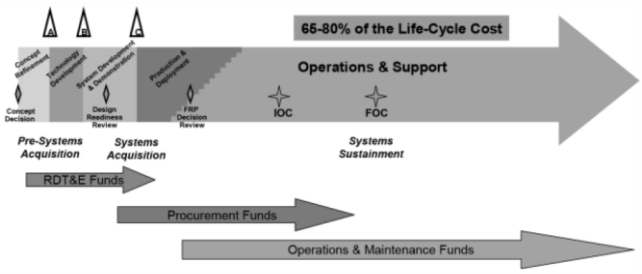

Fig. 1. The operating and support costs of military aircraft

The lessons learnt from the previous programmes have to be judiciously employed by Development Agency to cut down development cycle times. Incorporating most of the enhancements during prototype stage while leveraging field data would be crucial to improve key performance parameters related to availability and sustainability.

This paper discusses dovetailing of Service Lifecycle Management (SLM) strategy with existing enterprise systems to digitalise business processes required for meeting the above objectives.

II. FIGHTER AIRCRAFT DEVELOPMENT LANDSCAPE

A. Players

There are three major players in the Indian military aviation development scenario: User Services, Development Agency/OEM and Airworthiness Authorities [7]. Several PSUs, Research and Educational Institutes and Private Industries actively contribute to the programmes. Development progress is closely monitored by the Ministry of Defence.

B. Fighter Aircraft Lifecycle

The lifecycle of a fighter aircraft spans across decades comprising of different phases as shown in Fig. 2. In the first phase, based on the user requirements, a feasibility study is carried out by the Development Agency highlighting the features and the estimated performance of the fighter. The study also details out the timeline and cost. Upon project sanction by the Competent Authority, the Design, Development and Evaluation phase begins. This phase involves detail design, analysis, integration of systems, prototyping, flight testing and certification of the aircraft. Change and configuration management is critical here as this phase involves multiple changes and iterations in finalising the Standard of Preparation (SOP) of the aircraft.

Fig. 2. Lifecycle of a fighter aircraft

The certification by the Airworthiness Authority marks the beginning of the series production of the fighter. Amendments to SOP, modifications, deviations and concessions during production are normal. While in service, the aircraft undergo modifications, upgrades and repairs to overcome in-service obsolescence and/or to extend its useful life till their disposal. All these changes need to be managed by the Development Agency/OEM to provide continuous support in ensuring continued airworthiness.

III. DIGITAL FRAMEWORK: AS-IS SCENARIO

The development and operation of fighter aircraft happens based on the business processes laid out in "Framework and Procedure for Design, Development and Production of Military Air Systems and Airborne Stores" document (DDPMAS) and are closely monitored by the Airworthiness Authority. Many of these processes have been digitalised using enterprise systems such as ALM, MBSE and PLM for design and development; ERP for manufacturing and service and Enterprise Asset Management (EAM) for operation and maintenance. TejTESCT, an in-house tool for flight test scheduling and Computer Aided Maintenance Management System (CAMMS) for managing serialised physical structure of each prototype have been demonstrated [8]. Other niche tools are in use for simulation, analysis,

digital mock-up, virtual reality etc. but are not interfaced with enterprise systems. Many business processes are still document based and siloed. There are virtual walls between the enterprise systems, causing delay in flow of information. Field data are collected in digital/document format and stored independent of PLM. Configuration changes of aircraft are realised through document-based communications. This situation often causes data ambiguity and traceability issues. Logistics, service planning and technical publications are taken up much later in the lifecycle. Delivery of Technical Data Package containing all engineering data and descriptive documentation is either paper based or in digital formats not readily importable into EAM. Integrated decision support tools and management information systems are yet to be deployed, thus compelling the decision makers to rely on emails and documents.

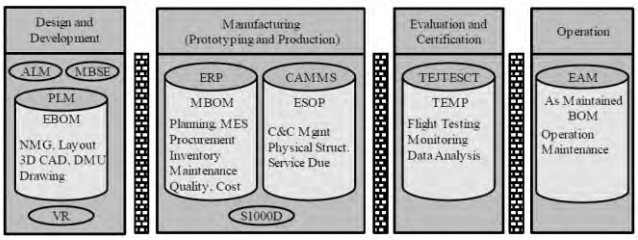

Fig. 3. Digital Framework: As-Is Scenario

IV. DIGITAL FRAMEWORK: TO-BE SCENARIO

In order to develop a sustainable aircraft with high operational availability (> 70%) and cost effectiveness, it is necessary to consider logistics, maintainability and support during the early phases of aircraft lifecycle. The user requirements for the upcoming programmes indicate evolution of maintenance strategy towards Condition Based Maintenance Plus (CBM+) philosophy. Use of data intensive techniques such as Prognostics and Health Management (PHM) becomes inevitable in this scenario. Related Reliability Availability Maintainability and Safety (RAMS) parameters have to be predicted during design, followed up during evaluation and improved upon by collecting operational data. This demands for a multidisciplinary team consisting of users, designers, manufacturing and flight test engineers to collaborate from the very beginning.

Interactive technical publications in S1000D standard are the next major activity that shall begin along with the product design. Data modularity and data reuse are the major advantages of S1000D. Authoring of data modules in an integrated framework would help update affected data modules necessitated due to the design changes. The same data modules can be reused in other type of technical documents and maintenance trainer simulators.

Frequent changes to the SOP of each aircraft during evaluation phase is common and can be better managed with the help of digital twins. Digital Twin ecosystem would facilitate quick support, collection of field data in real time and delivery of Technical Data Packages such as work cards, technical publications, master data and transactional data. This data can be readily ported to EAM so that the aircraft is made operational without delay.

When most of the data is available in structured digital format, it is possible to integrate Data Driven Applications to get insights about systems, manage concurrent programmes and speed up certification.
Digitalisation of end-to-end business processes in line with Industry 4.0 will go long way in establishing PHM, IoT and connected products. Flow of information through digital threads would facilitate accurate Change and Configuration Management and improves traceability.

A. Role of SLM in To-Be Scenario

SLM, being an extension of PLM, inherits configuration management capabilities. It is tailored to maximise product availability through Design for Service, Service Bill of Material (SBOM), Service Planning, Content Management, Digital Twins of physical assets, failure and performance data management. In addition, SLM would join the missing links between enterprise systems enabling digital data exchange.

The role of SLM during different phases of aircraft lifecycle are mapped below.

Design Phase:

- Facilitate creation of SBOM of aircraft, service planning and work cards in sync with Engineering Bill of Material (EBOM)
- Integrate S1000D content authoring tools with SBOM and host the content in a Common Source Database (CSDB), facilitating generation of Technical Publications along with product design
- Facilitate integration of decision making and data mining tools towards real time programme tracking and documenting for certification
- Provide a framework for Master Data Management of Line Replaceable Units (LRUs), Maintenance Significant Items (MSIs) & Tools Testers and Ground Equipment (TTGEs) along with their attributes such as embedded software and alternate parts
- Provide a framework for Maintenance Retex (Service Knowledge Management) using field data which can be used to improve PHM algorithms and RAMS KPIs
- Facilitate Long Term Archival and Retrieval (LOTAR) of data
- Enable change management of all the above through digital threads/workflows

Prototype & Evaluation Phase:

- Interface with ERP and facilitate creation of Digital Twin of each aircraft by instantiating LRUs and MSIs
- Enable change management of each aircraft structure (As-Maintained) after each aircraft activity
- Provide a framework for creation and management of technical documents like Certificate of Design, Flight Clearance Certificate, Request for Action, Request for Test, Work Done Report, Form 1090 etc. which are part of aircraft evaluation and certification
- Interface with TejTESCT to sync snag data and to provide insight into aircraft availability
- Trigger maintenance activity based on usage or fault codes
- Act as a test bed for Internet of Things, Artificial Intelligence and Machine Learning studies
- Following up of predicted RAMS parameters using Maintenance Retex and field data

Sustenance Phase:

- Interface with EAMs of User Services to maintain the Digital Twins
- Enable transfer of Technical Data Package along with each aircraft delivery such that the data can be readily imported into EAM
- Enable transfer of Service Bulletins and Support Requests
- Framework for field data capture and syncing with Maintenance Retex

With these in mind, the To-Be Digital Framework, after introducing SLM is as shown in Fig. 4. Each activity that needs to be taken up to realise the framework is explained in the following paragraphs with suitable examples.

B. Introduce SBOM

SBOM is a service-oriented digital representation of an ' service or that have an impact on service. The SBOM can be used to

- Define additional attributes related to maintenance such as alternate parts, embedded software versions, lot/serial numbers, dependency for removal/ installation etc. and facilitate Service Planning
- Break down the Bought Out Assemblies like Brake Assembly, Ejection Seat etc. into serviceable parts which otherwise are shown as single items in EBOM
- Simplify parts catalogue by clubbing loose parts into replaceable assemblies that can then be purchased by the User Services
- Link S1000D technical publications thus enabling change management and configuration control of the publications w.r.t. each aircraft produced
- Make available the latest design for downstream activities by establishing link with EBOM
- Create Digital Twin of each aircraft by instantiating serviceable parts via MBOM and manage the twin based on each aircraft activity
- Track equipment usage, trigger maintenance activity and enable digital data exchange

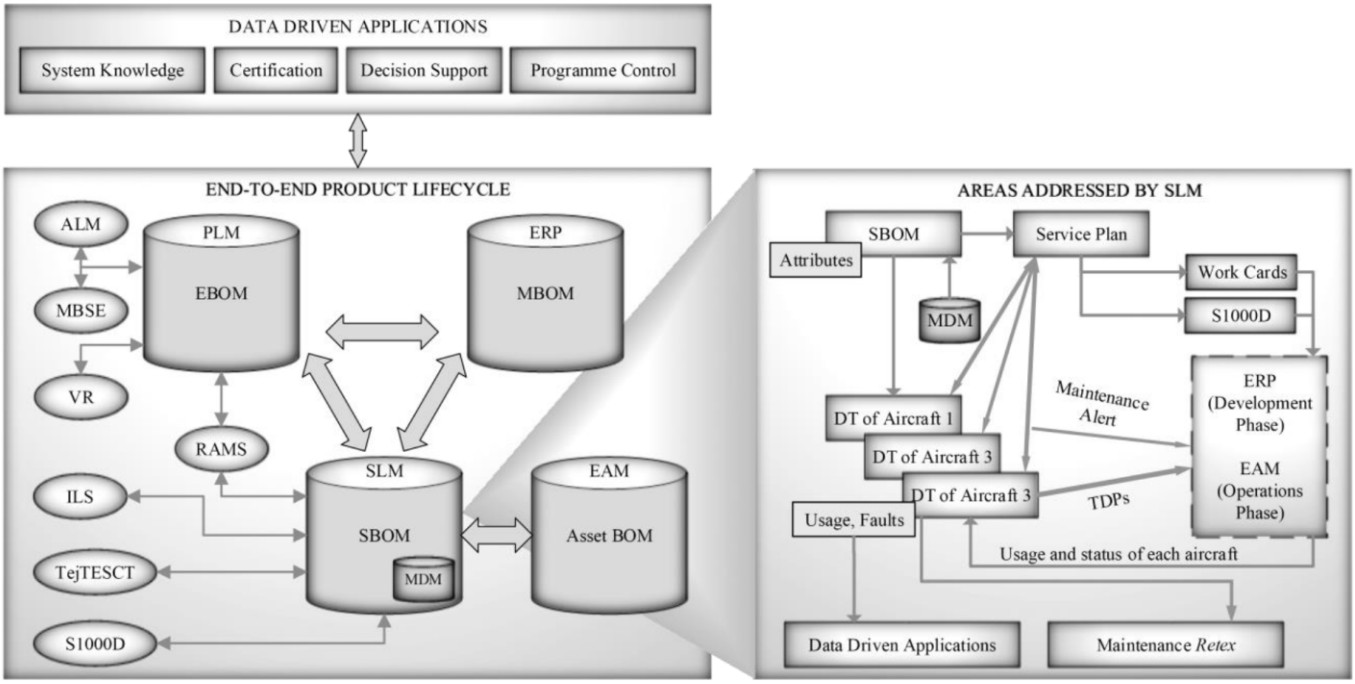

Fig. 4. Schematic of To-Be Digital Framework

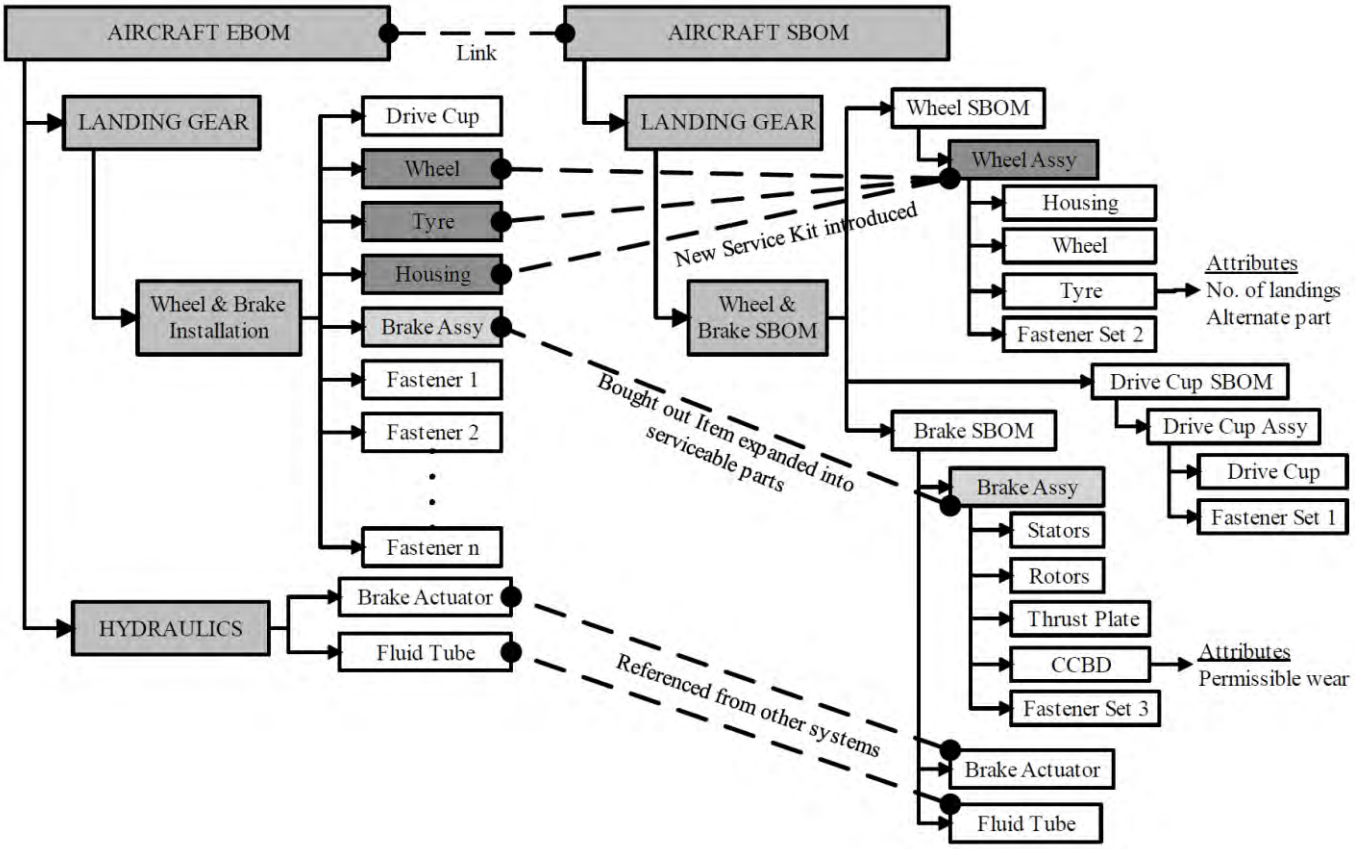

Fig. 5. Brake Assembly SBOM derived from EBOM

Building up of SBOM shall start along with the release of SOP of aircraft. Inputs required to build an SBOM are EBOM, MBOM, details of alternate parts, spare parts, attributes to be defined and maintenance resources. SBOM derived for a typical Wheel and Brake Installation is shown in Fig. 5.

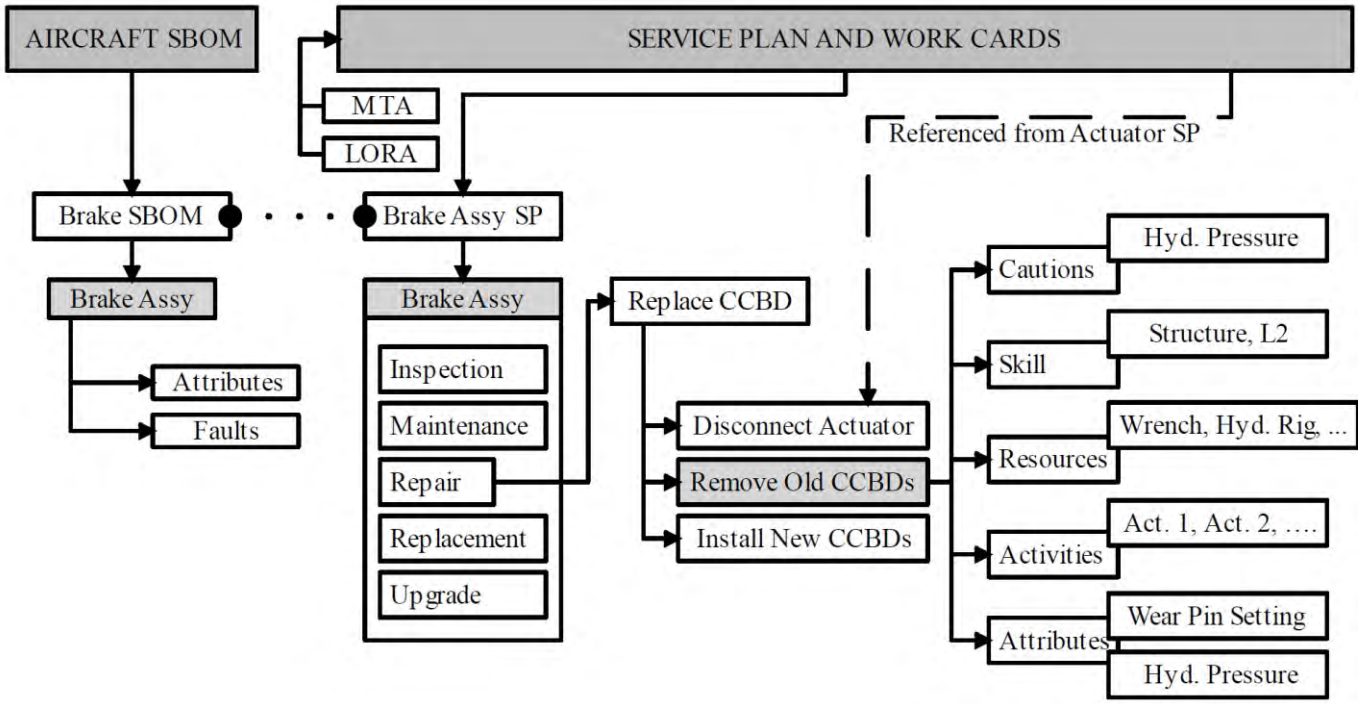

Fig. 6. A typical Service Planning for a Brake Assembly

The EBOM lists all the parts (Drive Cup, Wheel, Tyre etc.), Bought Out Assembly (Brake Assembly) and fasteners at the same level without segregating them into sub-assemblies. While generating SBOM, additional attributes (for e.g., permissible landings and alternate make for the tyres, permissible wear for the Carbon Carbon Brake Disk (CCBD); serial/lot numbers, time parameters required to track RAMS indices etc.) are defined. Based on the need, parts are clubbed into sub-assemblies (for e.g., Wheel Assembly is introduced by clubbing Housing, Wheel, Tyre and Fasteners) or broken down into serviceable parts (for e.g., Brake Assembly is broken down into an assembly of 5 parts). Hydraulic interfaces having an impact on servicing of Brake Assembly are referenced. Light weight CAD data are imported from EBOM into the respective parts in SBOM which are to be used for S1000D content authoring. SBOM is associated with EBOM to facilitate change management of downstream activities in case of design changes.

C. Master Data Management

Availability of accurate MRO Master Data (master data of spares, LRUs, TTGEs and consumables essential for keeping the aircraft operational) is critical for Service Planning. These data need to be de-duplicated and kept up-to-date by rationalising part identities and nomenclature of embedded software of LRUs, revising the parts based on form-fit-function principle, alias naming etc. A well-managed centralised database of these items within SLM can be readily referenced/used throughout aircraft lifecycle.

D. Service Planning

Maintenance of an aircraft involves activities to restore the aircraft to its operational state by means of service, repair or replace of systems/components of the aircraft. Service Planning helps derive types of services, their frequencies, removal/installations procedures for each of the serviceable items. Associated hazards, prerequisites, skill sets, resources and checks are associated with the service plans. Maintenance Task Analysis, Level of Repair Analysis and historical data are the major inputs to the Service Planning. These service requirements are linked directly to associated parts and assemblies in the SBOM to maintain traceability. Digital Work Cards can be generated out of this structured information. When linked with the Digital Twins, maintenance can be triggered based on fault codes or usage. In conjunc-

tion with IoT and Predictive Maintenance, aircraft-on-ground time can be minimised by keeping the tools, spares and skills ready before an aircraft lands. Service Planning is the major input for S1000D Technical Publication authoring. A typical Service Planning for a Brake Assembly is shown in Fig. 6.

E. S1000D Technical Publications

Technical Publications are critical to execute service and flight operations. More than 20 types of flight and fleet publications are in use apart from numerous technical documents that have to be maintained towards aircraft certification.

In the integrated digital framework, S1000D Technical Contents such as system specifications, 3D/2D geometry, graphics, procedure modules, translations etc. can be organised as Publication Bill of Material (PBOM). By integrating content authoring tools with PBOM which is linked to SBOM and Service Planning, it is possible to leverage existing engineering and service information to deliver accurate and configuration specific interactive manuals. Reuse and modularity are the advantages of S1000D contents. These can be effectively reused in maintenance training simulators as well as in generating other types of technical documents

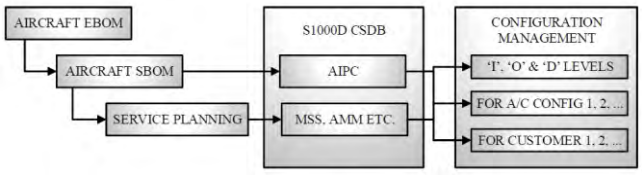

Fig. 7. Methodology to derive S1000D Technical Publications in SLM

F. Digital Twins

Digital Twin is the digital replica of an aircraft that includes specifications, engineering models and more importantly the as-built and as-maintained data unique to that aircraft. Though a variety of Digital Twins can be configured to address defined objectives, As-Maintained Twins, RAMS Twins and Lifecycle Cost Twins are more relevant w.r.t. sustainability.

Throughout the evaluation and certification phase, the configuration of aircraft changes frequently due to design improvements, replacements, cannibalism, flight test needs etc. Same is the case during operation phase but mostly due to upgrades, replacements and repairs. LRUs and MSIs of an SBOM can be instantiated by syncing their attributes with MBOM to have an As-Built Digital Twin for each of the aircraft produced. Further, As-maintained BOM can be managed by initiating the configuration change process of the aircraft from within the SLM. This eliminates the document based change management and ensures traceability and historical configurations of that aircraft. These data are invaluable during defect investigations, upgrades and life extension of aircraft. The data pool thus collected can be fed into RAMS and Lifecycle Cost Twins to continuously monitor and improve the products.

G. Maintenance Retex

Retex '*The Return of Experience*' – feedback from the field in this case. RAMS analysis carried out during the design phase is either based on *physics of failure* or model based approach. This analysis is validated by collecting field data over a period of time. Problem areas are identified and fixes found either by improving design or by augmenting support. Moreover, CBM+ philosophy requires adoption of data dependent PHM techniques to predict failures during operations so that preventive measures are taken before aircraft go unserviceable.

To achieve this, a 'clean ' digitised pool of field data is required. By mapping field data with aircraft Digital Twins via Digital Thread, it is possible to maintain and aggregate the data pool which then can be used to fine-tune the analysis, improve PHM algorithms and feed *Data Driven Applications*.

H. Data Driven Applications

Availability of structured digital data opens doors to integrate *Data Driven Applications* within the digital framework to provide actionable insights across lifecycle. Interactive illustrations and dashboards would feed all the stakeholders with correct information and helps decisionmaking. Dependency on document based decision mak-

ing is reduced considerably thus saving time and resources being employed in digging out the right information.

V. THE ROADMAP

The work of realising an end-to-end digital framework is complex in nature and massive in scale, spanning across years and thus needs to be taken up in phases after developing a detailed roadmap. The strong will of the management for a cultural shift and careful selection of solution partners are vital for its success. Long term MoUs with the solution partners w.r.t. licencing and support and agreements between OEM and Users for data sharing makes the implementation process smoother. Pilot studies and proof of concept projects in the sub-areas provide insights into probable problem areas which then can be addressed during implementation.

VI. CONCLUSIONS

The studies demonstrated so far [8 & 9] backed by further technological advances in the area confirms that it is possible to have an end-to-end Digital Framework to manage complicated aircraft programmes having long lifecycles. Such a digital framework is the key in achieving the following:

- To establish collaboration between all stakeholders throughout the lifecycle of the fleets
- To minimise acquisition time, maximise utilisation, reduce lifecycle costs and to use field data to improve the products
- To have a common understanding of all aspects of lifecycle including logistics, time, cost, schedule, quality and risk
- To introduce decision making tools with end-to-end tracking capabilities, analytics and reporting
- To realise real time data exchange (master data, transactional data, publications, service bulletins and failure data) between enterprise systems of aircraft OEM and owners/operators
- To facilitate upgrades (technology insertion), repairs, defect investigations, device a PBC policy and life extension of products through LOTAR
- A test bed for deploying IoT, AI, ML techniques to realise Connected Products

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