

Simulation-Driven Development and Validation of an Automotive Lower Door Trim and Map Pocket

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Abstract—Automotive interior components such as lower door trims and map pockets are required to meet stringent functional, structural, aesthetic, and manufacturing constraints while remaining cost-effective for high-volume production. Achieving this balance demands an integrated development approach that connects design intent with engineering validation and manufacturing feasibility. This study presents an industry-oriented framework for the design and validation of an automotive lower door trim with an integrated map pocket, developed using a polypropylene-based material system. The proposed methodology integrates Class-A surface extraction, tooling axis definition, DFMA-based feature development, finite element analysis under multiple loading conditions, and injection molding process optimization through moldflow simulation. Prototype development using rapid prototyping and aluminium soft tooling was carried out to validate form, fit, function, and process reliability prior to production tooling. Key findings demonstrate that the optimized component achieved an 8% reduction in weight through topology optimization while maintaining structural integrity under static, impact, door-slam, and thermal loading conditions. Manufacturing optimization resulted in a 22% reduction in cooling time, significantly improving cycle time and production efficiency. The finalized design met the target cost of manufacturing at ₹ 235 per part of around 6% below the target cost confirming the economic feasibility. Comprehensive prototype testing of the product included mechanical durability, environmental resistance, functional reliability, and ergonomic usability along with all test criteria successfully meeting these requirements. The study creates a validated and production-ready solution and delivers a scalable development framework that is an effective bridge between the digital engineering and series production of automotive interior trim components.

Index Terms—Automotive interior components, Finite element analysis, Injection molding optimization, Lower door trim design, Prototype validation.

I. INTRODUCTION

Over the past several years, the automotive industry has gradually been enhanced by innovative polymer composites and natural fiber reinforced materials for their lightweight, cost-effective and environmentally friendly characteristics which are the transition from ordinary synthetic materials to biological materials [1], [2]. This evolution is in harmony with growing regulatory values and consumer demand for sustainable products, with studies showing up to 35% cost reductions and significant reductions in carbon footprint with the novel application of materials [3]. This has its practical significance in realizing an aesthetic quality, functional durability, and environmental responsibility, which is crucial in competitive automotive design [1], [4]. The particular problem solved is to optimise the design and material choice to create lower door trims and map pockets meeting stringent functional and aesthetic requirements while minimising environmental impacts. Despite the development in moulding in colour plastics and moulding natural fiber composites, gaps are still present in the knowledge of how to do this without compromising mechanical performance and recyclability [5], [6]. There are conflicting views on the trade-offs between durability and biodegradability and the cost implications of adopting bio-based composites in place of conventional plastics [7], [8], [9]. The consequence of such gaps is underutilizing of sustainable materials in industries, as

well as failing to see the opportunity for the sustainable development of car environment footprint [10]. Key concepts include mold-in-color technology, natural fiber reinforced polymer composites, and life cycle environmental assessment which are collectively used to make design decisions aimed at improving performance and environmental results [11], [12]. The framework emphasizes the synergies between material properties, processing routes, and environmental impacts to instructively assess design alternatives in a systematic way [13], [14], [15].

II. SUMMARY OF THE PREVIOUS STUDIES

The table 1 shows research landscape of the literature on Plastic product design of lower door trim and map pocket focusing on design materials and techniques, functional and aesthetic considerations, and environmental and sustainability factors. The

reviewed studies cover a wide range of materials such as conventional plastics, bio-based composites, and natural fiber reinforced polymers with methodologies varying from experimental fabrication, mechanical testing to life cycle analysis and computer simulations. Table 1 Literature Review

The geographic and disciplinary interest is varied in itself (automotive engineering, materials science, sustainability research) which is in line with the interdisciplinary nature of the automotive interior component design. This comparative analysis is the answer to the research questions by massaging the information regarding the material performance, aesthetic quality, environmental impact, manufacturing efficiency and functional integration to identify current trends and gaps in sustainable automotive design of the trim. Table below shows literature review.

Study	Material Performance	Aesthetic Quality	Environmental Impact	Manufacturing Efficiency	Functional Integration
[8]	Sustainable injection molding decreases waste and emissions	Focus on material choice to boost aesthetics	Promote the use of bio polymers and biodegradable polymers	Hybrid molds and process optimization	Boost circularity of the product and its functionality
[12]	NFRPCs exhibit competitive mechanical and thermal properties	Natural fibers provide acceptable interior aesthetics	Life cycle assessments show reduced ecological footprint	Manufacturing challenges and additive treatments discussed	Functional performance enhanced by fiber-matrix compatibility
[16]	Bamboo fiber and talc composites improve mechanical properties	Enhanced surface compatibility and texture	Higher environmental impact due to fiber processing	Injection molding process studied for efficiency	Good friction and wear properties for interiors
[17]	Surface treatments enhance polystyrene composite strength	Improved gloss and color stability with treatments	Supports circular economy and sustainability	Manufacturing methods impact composite quality	Functional for automotive interior applications
[4]	Comprehensive design strategies for strength and stiffness	Discusses surface finish options, design for aesthetics	Addresses life cycle and recycling concerns	Reviews multiple manufacturing processes	Emphasizes design for assembly and function
[18]	Biobased composites with natural fibers show good mechanical properties	Natural fiber texture influences aesthetics positively	Biodegradable, renewable, eco-friendly materials	Various advanced manufacturing techniques reviewed	Design parameters optimize composite properties

Study	Material Performance	Aesthetic Quality	Environmental Impact	Manufacturing Efficiency	Functional Integration
[19]	Natural fiber-epoxy composites show high tensile and erosion resistance	Surface treatments improve mechanical and visual quality	Sustainable and recyclable composites	Mechanical and erosion testing performed	Functional for automotive applications
[7]	Bio-based plastics face design and recycling challenges	Limited aesthetic adoption in durable products	Barriers include cost and recycling infrastructure	Design strategies for bio-based plastics	Functional design must consider lifecycle
[20]	Plant fiber composites improve strength and reduce weight	Surface treatments improve visual appeal	Sustainable, biodegradable, and renewable composites	Hybridization and nano-fillers improve processability	Addresses automotive body part functional needs
[21]	Lignocellulosic composites show promise but need durability improvements	Aesthetic potential with natural fiber composites	Cost-effective and environmentally friendly	Processing techniques impact performance	Focus on overcoming fiber-matrix compatibility issues
[1]	Plastics contribute to weight reduction and safety	Advances in plastic aesthetics and smart materials	Highlights recycling and circular economy	Emerging sustainable plastic technologies	Functional design supports automotive safety and comfort
[22]	Natural fibers reduce weight and cost in composites	Natural fiber composites offer unique textures	Environmental burden reduced by fiber substitution	Established composite manufacturing processes	Used in door panels and interior components
[15]	Graphene-enhanced PP composites improve strength and reduce weight	Maintains surface quality suitable for interiors	95% CO2 reduction via waste PP upcycling	Efficient injection molding with improved flow	Meets automotive interior part mechanical demands
[23]	Bamboo fiber-PP composites optimized for strength	Natural fiber aesthetics with improved surface quality	Life cycle assessment identifies carbon hotspots	Compression molding parameters optimized	Functional for automotive structural parts
[24]	PP-paper composites show good flexural and impact strength	Paper fibers provide distinct natural aesthetics	Low carbon footprint and water uptake	Hybrid wet-lay/compression molding optimized	Suitable for automotive interior applications
[25]	Nanoscale modifications improve NFC mechanical properties	Enhanced thermal stability and aesthetics	Biodegradable and renewable materials	Molecular dynamics simulations guide design	Functional applications in automotive sectors
[26]	Natural fiber composites exhibit recyclability and adaptability	Mechanical properties comparable to traditional composites	Environmentally safe and sustainable	Chemical treatments improve processing	Broad engineering applications including automotive

Study	Material Performance	Aesthetic Quality	Environmental Impact	Manufacturing Efficiency	Functional Integration
[14]	Composite design reduces carbon footprint in automotive parts	Design for sustainability includes aesthetics	Life cycle assessments guide material selection	Emerging technologies improve manufacturing	Balances lightweighting and environmental goals
[9]	Fully bio-based composites show promising mechanical properties	Bioprepregs offer improved aesthetics	Biodegradable and renewable materials	Various bio-based processing techniques reviewed	Functional for automotive interior applications
[27]	NFCs provide competitive mechanical and physical properties	Natural fibers offer cost-effective aesthetics	Biodegradable and lightweight composites	Overview of fabrication methods	Applications in automotive and packaging
[2]	Biofiber composites reduce weight and improve efficiency	Natural fibers provide desirable aesthetics	Environmentally friendly alternatives	Used in dashboards, door panels, pockets	Functional for automotive interior components
[13]	Lightweight PP blends with talc, good mechanical properties	Standard automotive finish, no special aesthetic focus	Supports lightweight design, indirect environmental benefits	Cost-effective low-density material, easy processing	Suitable for door panel structural requirements
[11]	NFPCs exhibit superior mechanical and tribological properties	Surface treatments enhance aesthetics	Biodegradable and flame retardant composites	Advanced fabrication methods reviewed	Functional for high-temperature applications
[28]	Optimized oat-hull PP composites balance properties	Cost-effective natural fiber composites	Eco-friendly with minimized cost	Statistical mixture design applied	Suitable for automotive applications
[29]	Sisal fiber composites improve impact resistance	Alkali treatment enhances surface properties	Lightweight and biodegradable composites	Compression molding with factorial design	Functional for light automotive parts
[6]	Bio composites High performance and degradability	Bio-based matrices for aesthetics	Environmental and economic benefits	Commercial scale challenged,	Functionality Interiors and exterior parts

III. RESEARCH GAP

Recent progress in automotive interior design aspects, which focus on convergence of light waiting, functional integration, manufacturability as well as sustainability, can be seen in high volume plastic components such as lower door trims and map pockets. Prior studies have largely been limited to innovations at the materials level, regarding the development of novel bio-based polymers, natural

fiber-reinforced composites, and mold-in-color technologies, or have been limited to isolated consideration of aspects of aesthetics and environmental performance, often failing to validate their applicability through full-scale component design, structural verification and production feasibility. In contrast, the present study bridges this gap by integrating established polymer materials (PP-based systems) with a comprehensive, industry-oriented design and validation workflow that

encompasses Class-A surface development, detailed engineering feature design, finite element-based structural optimization, mold flow-driven manufacturing refinement, and prototype-level testing. While literature reports the potential of sustainable composites and advanced processing techniques to reduce environmental impact and component weight, their adoption is frequently constrained by concerns related to durability, cost, recyclability, and process reliability. The project report responds directly to these constraints by proving that, by using a conventionally viable material system, rigorous application of DFM principles, FEA-based results optimization, and control of the injection molding process, tangible results can be achieved in terms of weight reduction, cost efficiency, structural performance, and production cycle time. Moreover, in contrast to many previous works which are still in the conceptual stage or at the material testing level, the design decisions are validated using the mechanical, environmental, ergonomic, and manufacturing performance criteria, which provide a practical and scalable framework for automotive interior trim development. This alignment supports the contribution-from research in this article as an application-driven extension of existing research in the area, where theoretical content and design knowledge can be translated into a production-ready automotive component solution.

IV. METHODOLOGY

The adopted methodology of the Fig 1 presentation consists of systematic and industry-based workflow of the development of an automotive lower door trim with an integrated map pocket. This starts with establishing design goals, Class-A surface extraction and substantial tooling axis style analysis to guarantee aesthetic quality and manufacturability. Class-B and Class-C surfaces are then fabricated to make a closed solid model, and then engineering characteristics are provided into the design using DFMA principles to improve structural performance and construction efficiency. The selection of materials is conducted using PP-T20 due to its mechanical property, cost-effectiveness and the ability to use in injection molding. Structural integrity is checked by the use of finite element analysis under various loading conditions and manufacturing viability is checked by

injection molding and mold flow analysis. Lastly, prototype development and testing would verify satisfactory design in terms of functional requirements, structural requirements and production requirements.

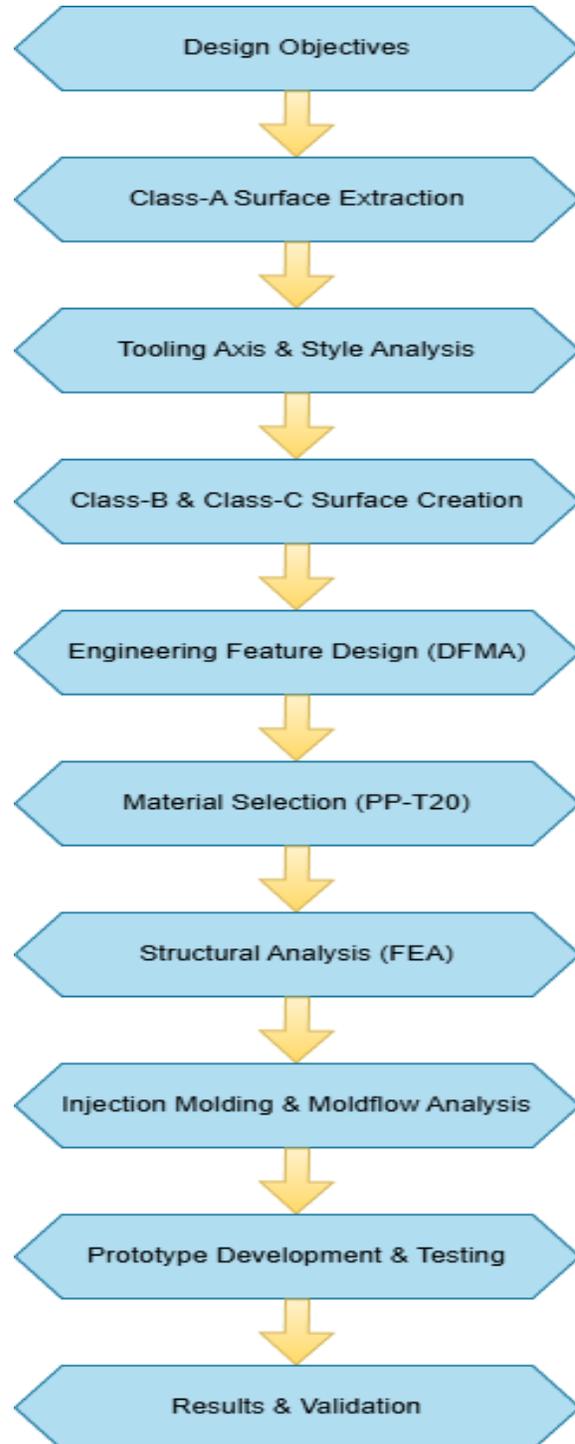


Fig 1 Methodology Flow Chart

V. DESIGN STEPS

After the style (3D cad surfaces) are received these are the following steps carried out while designing the plastic part.

A. *Extracting the Class, A surfaces.*

When the style is received, the whole door style is received from the styler. We have to cut the style according to the parts. Hence, we need to extract the surfaces of style for the further use of design. Fig 2 shows the details.

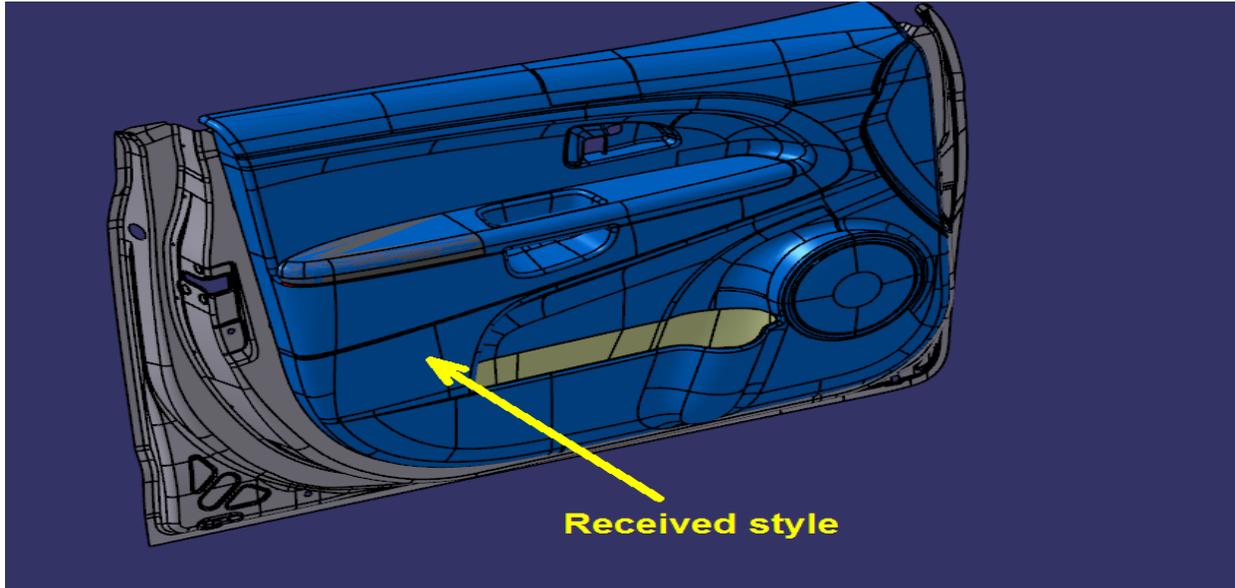


Fig 2 Class – A Surface

B. *Creation of tooling Axis*

This tooling direction is kept parametric, so that we can change it according the draft analysis. Details of tooling directions are shown in fig 3.

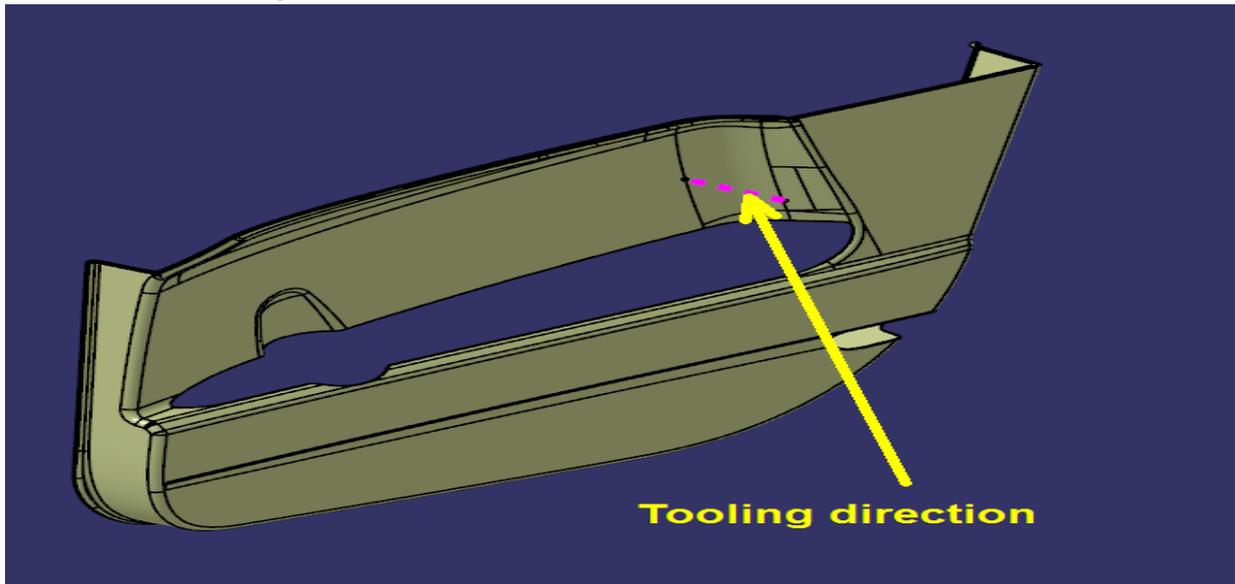


Fig 3 Tooling direction

C. *Style analysis of Class A surface*

In this analysis the merging distance between the all engineering surfaces (style surfaces) are checked. Depending upon various OEM the merging distance can be varied. Style analysis shown in fig 4.

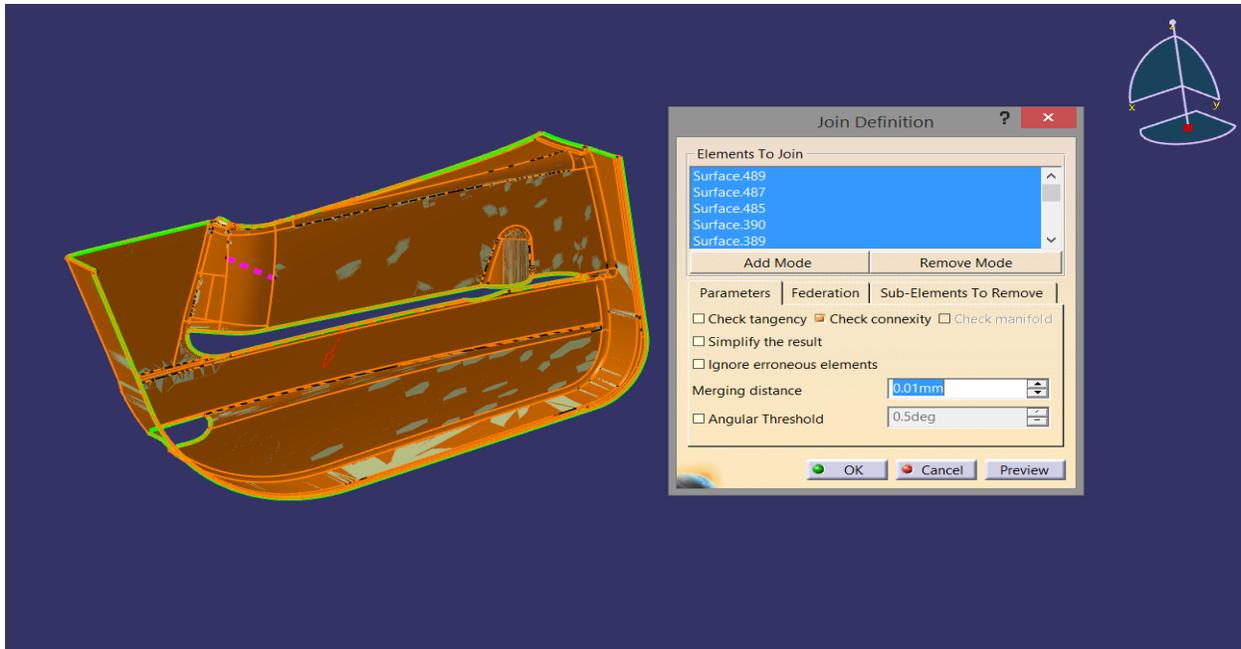


Fig 4 Merging of style.

Below Fig 5 shows draft analysis helps to check that in tooling direction we have created all style gets cleared so that it might not create a problem for manufacturing purpose. Draft analysis is done on A side by keeping value from 3 degree to 7 degree depending upon manufacturing process and graining. There is graining on A surface of some parts and that graining need some specific draft to get covered for manufacturing, to check weather that draft is cleared or not we need to check that in full analysis. This is the analysis to check draft. Some of the manufacturing process require specific draft on A side.

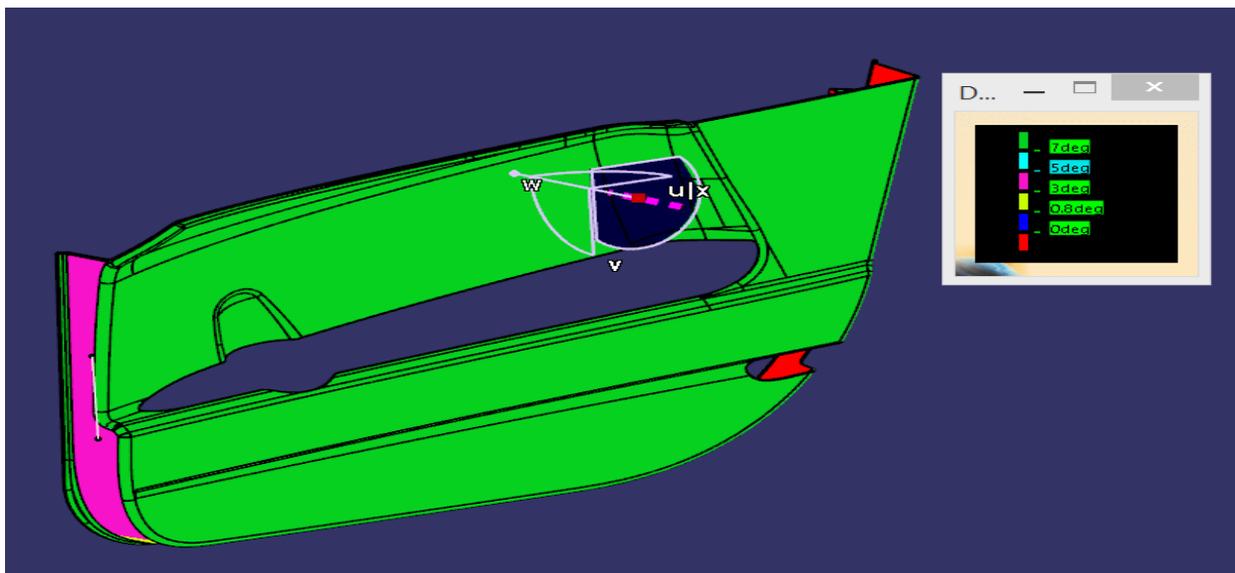


Fig 5 Draft analysis.

Radius of curvature analysis on plastic parts is a critical process in design, manufacturing and quality control, particularly in industries like automotive, aerospace, etc. It includes the evaluation of the curvature of surface or edge curvatures of plastic components to make sure that they meet functional, structural and aesthetic requirements. Curvature analysis ensures mold cavities have appropriate radii to prevent stress concentrations or flow issues during molding. Details are as follows in fig 6.

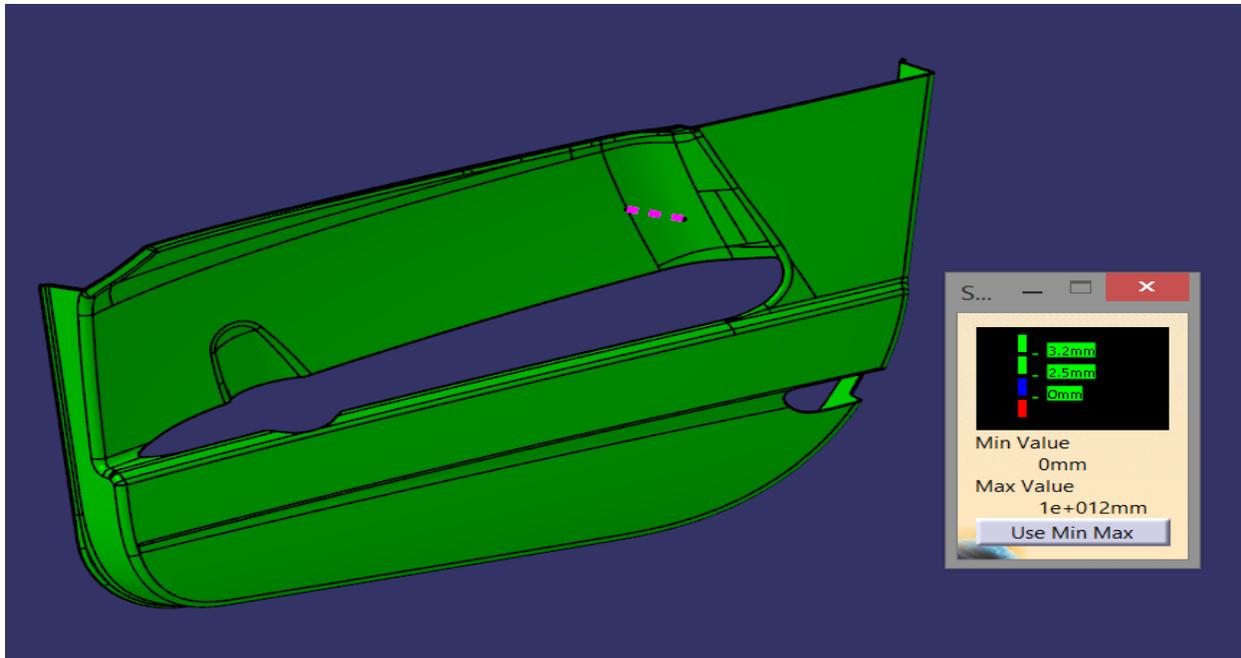


Fig 6 Radius curvature analysis

D. Under Flush

Definition: A panel or component that is recessed or sits slightly behind the adjacent surface.

Visual Description: Imagine a car door that doesn't quite sit level with the body of the car; instead, it appears to be set back slightly. This can create a shadow effect along the edge.

Example: If a door panel is under flush it may not meet the fender and there is a gap which would be less visually attractive.. See Fig 7.

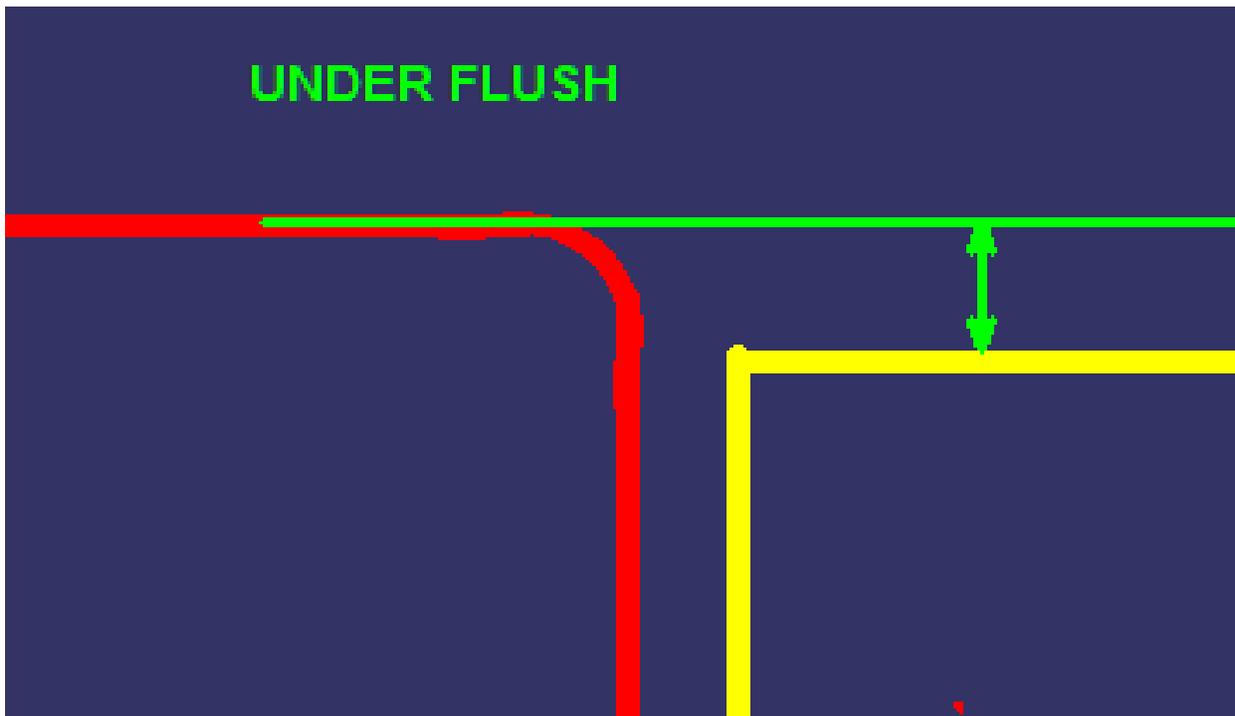


Fig 7 Under Flush

E. Over Flush

Definition: A panel or component that protrudes beyond the adjacent surface.

Visual Description: Picture a hood that sits higher than the fenders, creating a noticeable bump or bulge at the edges. This may lead to a misalignment that affects both aesthetics and functionality.

Example: If a trunk lid is over flush, it might extend beyond the rear fenders, disrupting the smooth lines of the vehicle. fig 8 and 9 shows more information.

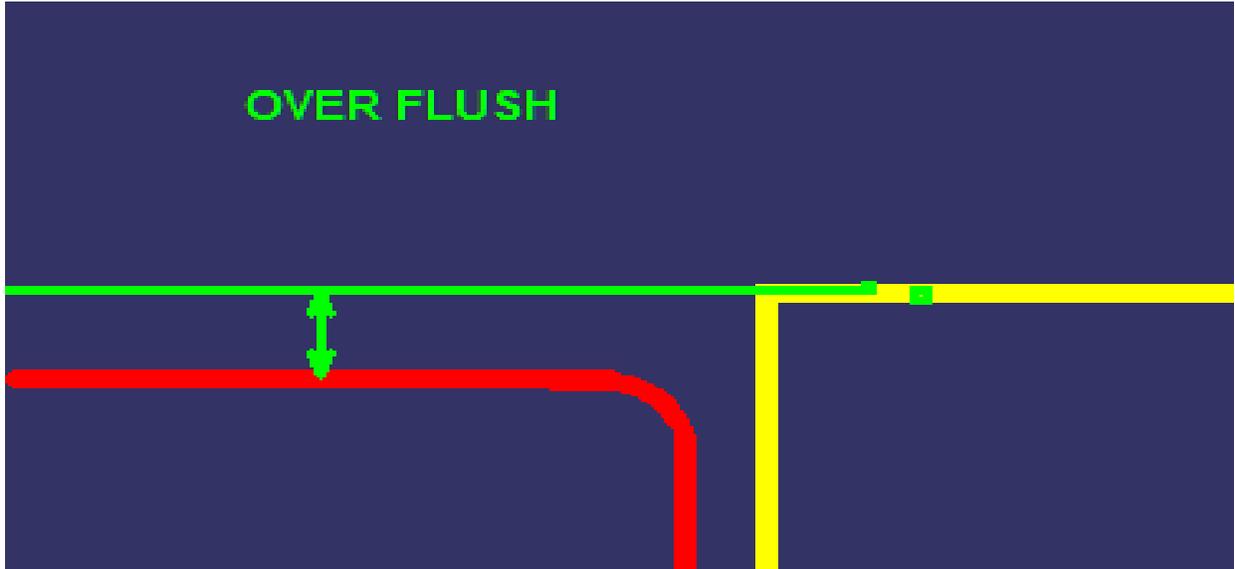


Fig 8 Over Flush

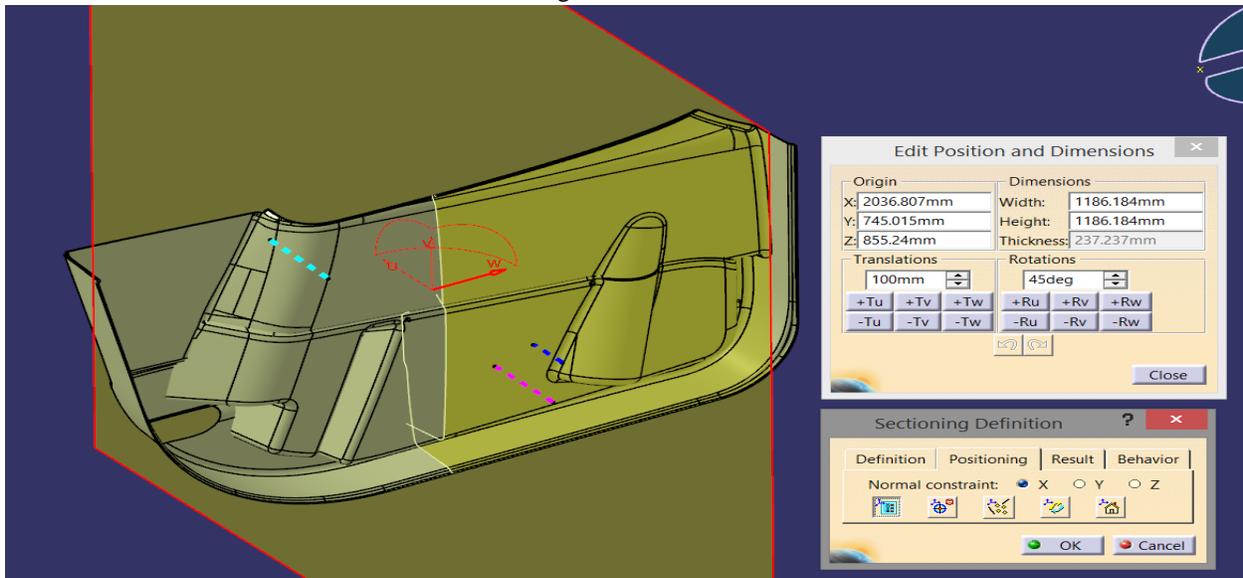


Fig 9 Details of flush

F. Creation of Class-B surface

Fig 10 describes B surface is created by offsetting the Class A surface by the component's thickness and adding engineering features like ribs, bosses, and locators, which are designed to be non-visible and are often created first and then blended into the base surface. The process typically involves extracting surfaces from the Class A surface, creating features like ribs, extruding or offsetting them, and then joining them all together to form the B surface. According to the thickness of part, B surface is created by offsetting the A surfaces by 2.5mm.

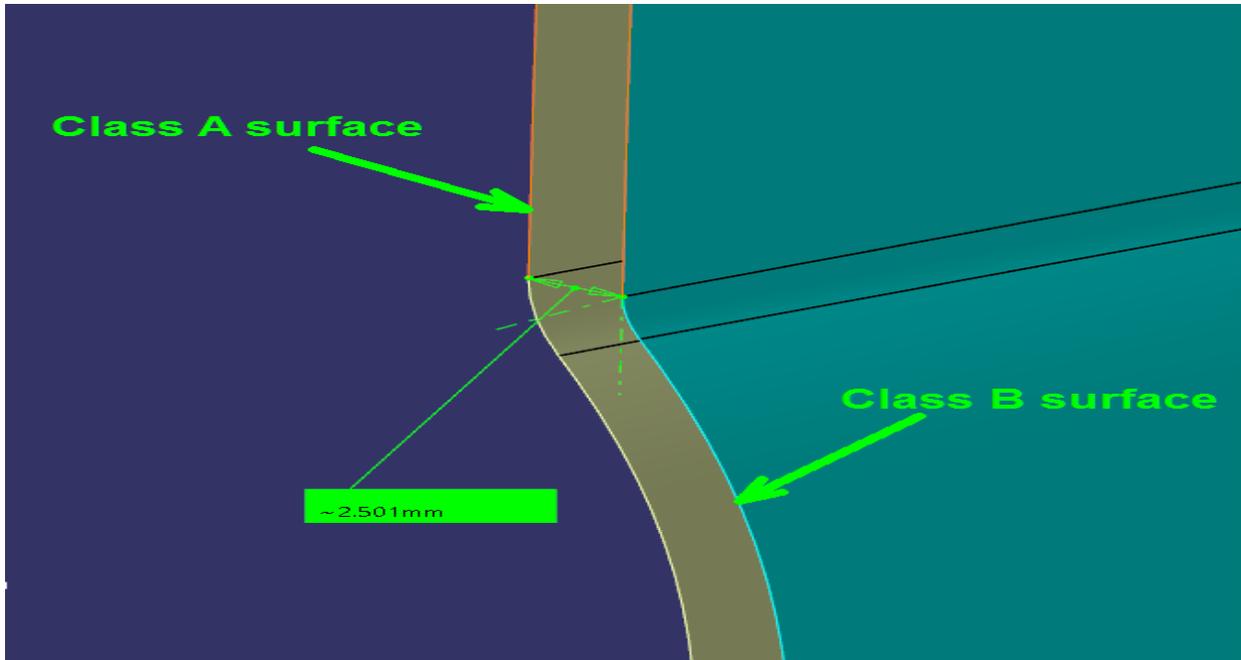


Fig 10 Class – B Surface

G. Creation of Class-c surface

To make a solid body we need to close the A and B surface. So closing surface i.e C surface is created. Details are as shown in fig 11.

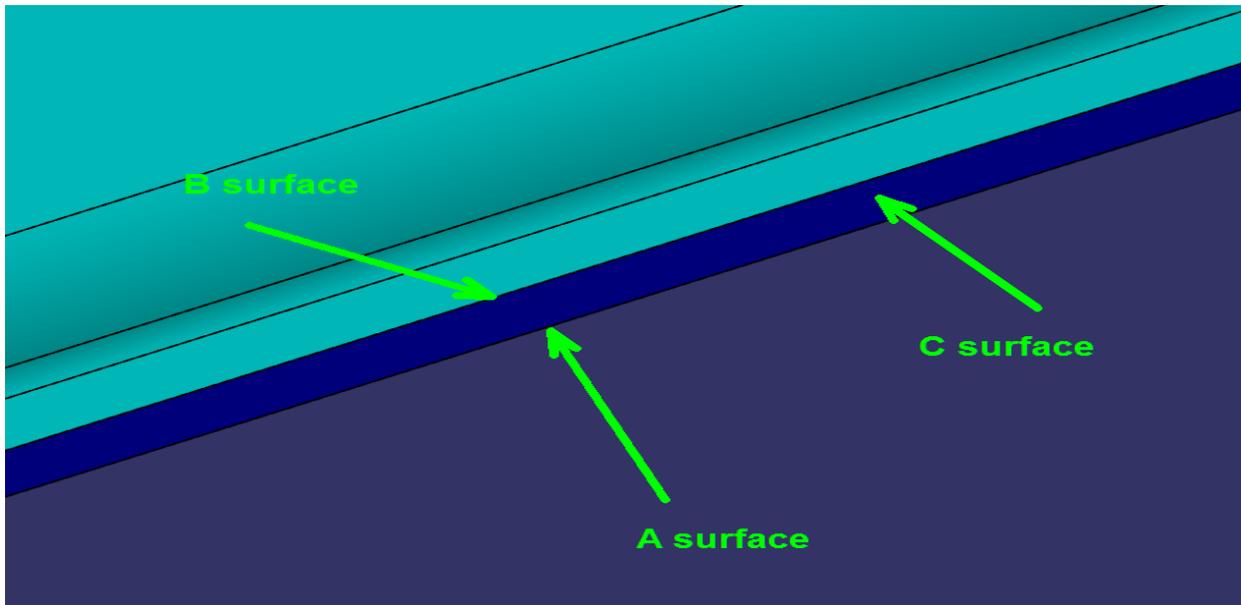


Fig 11 Class – C Surface

H. Addition of Features

Depending upon the environment and fixation strategy, the features are decided to be trim with plastic part. Hence with BIW doghouse and clip is used, with plastic part welding cylinder is used, and for reinforced part screw boss is used. See fig 12.

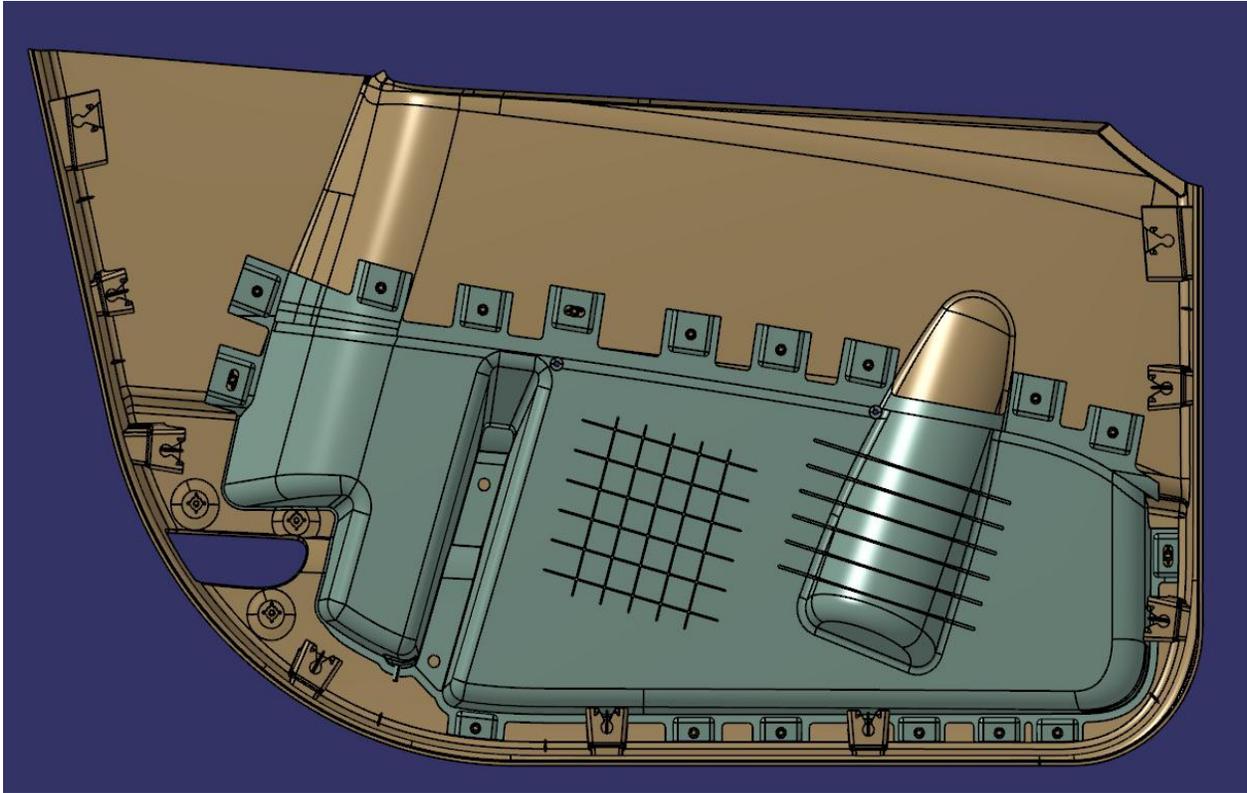


Fig 12 Addition of Features

I. Structural Analysis And FEA

Structural performance of lower door trim and integrated map pocket were analyzed using Finite Element Analysis (FEA) to determine stress, strain and deformation behavior under realistic service conditions. The main goals of the analysis were to confirm structural integrity under operation loads, to identify critical areas of stress concentration, material distribution optimization, as well as prediction of deformation before physical prototyping. Multiple loading scenarios were simulated such as static loading with 5 kg mass applied to the map pocket under the influence of gravitational acceleration, impact loading which corresponded to 10 J energy drop over 50 mm contact zone, door slam loading which corresponded to a 50 N distributed pressure, thermal loading over a temperature range of [?]40 degC to +85 degC to account for the environmental effects. The model was discretized with tetrahedral elements (SOLID187) global mesh size of 3-5 mm and local refinement of 1 mm in critical regions. Mesh quality was controlled with an aspect ratio less than 5 and orthogonal quality greater than 0.3, which has

about 250,000 elements and 450,000 nodes to get accurate and reliable simulation results.

J. Manufacturing Process Design

The design of the manufacturing process was made on the injection molding machine with the 650 tons of clamping force machine capacity, 1500 g shot capacity, and 1800 bar injection pressure to guarantee the molding of lower door trim and integrated map pocket. A configuration of a two-cavity family mold was adopted, with combination of the map pocket and lower trim to improve production efficiency, and was supported by the hot runner system with the valve gate to achieve the balance between the flow and the wastage of materials. Side actions were done to adapt to undercuts and a conformal cooling system based on water at 25 degC with a flow rate of 12 L/min allowed good heat dissipation. This cooling strategy therefore shortened the cooling time from 45 s to 35 s, which contributed to a total cycle time of 52 s. The optimized process parameters, such as melt temperature of 220degC, mold temperature of 40degC, injection speed of 80mm/s, packing pressure of 600bar and packing time of 8s, ensured consistent part quality,

dimensional stability and repeatable manufacturing performance.

K. Prototype Development and Testing.

Prototype development and testing was done to validate the design before series production. Initial design verification was done using rapid prototyping with stereolithography (SLA) using Accura 55 resin to check form, fit and functional requirements. This was followed by soft tooling using aluminium molds to produce a pilot batch of 50 components to allow the process to be validated in near-production conditions. The developed prototypes were tested in an extensive testing protocol, which included mechanical, environmental and functional tests. Mechanical testing demonstrated the adequate structural performance with static loading (5kg for 24h) maximum deflection 3.1 mm and impact and fatigue testing revealed no cracking and no structural failure. Environmental tests such as temperature cycling/humidity exposure UV aging showed dimensional stability and acceptable surface durability. Functional testing further tested assembly performance, along with user interaction and snap fit forces were within the stipulated range and ergonomic testing indicated the tool was highly accessible and ease to use confirming the robustness and production readiness of the component.

VI. RESULT AND DISCUSSION

The achieved results at the design, analysis and the validation stages illustrate that the proposed lower door trim and the integrated map pocket successfully achieve the targeted functional, structural and manufacturing requirements: The finalized component came in at a weight of 782g which is an 8% reduction over the initial design whilst maintaining the strength of the structure. This decrease was accomplished mainly by FEA-driven optimization of the ribs and material distribution, demonstrating the usefulness of simulation-based design optimization.

Structural analysis results prove that the maximum deformation under static loading of 5 kg was restricted to 3.2 mm which is well within the allowable value of 5 mm. The maximum von Mises stress recorded was 18.5 MPa, giving a factor of safety of about 1.6 which is sufficient strength for normal conditions of usage. Impact and door-slam loading situations further proved that the peak stresses did not exceed the

material yield strength and no permanent deformation could be observed, which proved PP-T20 to be a suitable material for this application. Manufacturing feasibility was verified by moldflow analysis, which demonstrated uniform filling of the cavities at a fill time of 1.8 s with minimal weld lines confined to areas that are not critical, and controlled sink marks less than 0.2 mm. Warpage was limited to 0.45 mm which assures dimensional stability and acceptable surface quality for visible interior components. Optimization of the design of cooling channels led to a 22% improvement in cooling time which directly influenced the efficiency of production

Prototype testing confirmed the simulation results as all of the samples were able to pass mechanical, environmental and functional testing with no sample failure. Ergonomic evaluation resulted in high scores for user satisfaction which confirmed ease of access and usability of the map pocket. From the economic point of view, the optimized design was below the target cost of Rupees 235 per part, and demonstrated manufacturing cost was below the target, making the design commercial. Overall, results validate the integrated design-analysis-manufacturing strategy for the automotive interior trim development introduced in this study as an effective and scalable tool.

VII. CONCLUSION

This is a research work that has shown structured and industry aligned method for the development of an automotive lower door trim and integrated map pocket with special focus on the integration of the design quality, engineering robustness and manufacturability. Rather than approaching design, analysis and production as separate phases of a project, the study emphasizes the need for a whole-of-workflow approach to integrate the Class-A surface integrity with downstream engineering decisions, ensuring that there is no inconsistency between the styling intention and the functional performance. A major takeaway from this work is how paramount it is to have DFMA principles in mind early enough, with simulation-driven validation, to greatly improve the reliability of the design while minimizing cycles of iterations in the tooling and production stages. The systematic application of FEA and moldflow analysis has allowed informed decision making relating to material distribution, feature placement, and process

parameters, which avoids the trial-and-error approaches commonly seen in conventional trim development practices.

Beyond the particular component studied, the results have wider implications for the development of the automotive interior, where at the same time the increasing demands for light weight, cost control and high perceived quality need to be met. The production-ready solutions presented in this study show that they may be obtained with already known polymer systems if they are backed by robust digital engineering tools and disciplined design methodologies. The main contribution of this work would be the presentation of a validated end-to-end development framework that bridges this gap between the conceptual design and series production. Unlike portions of research that are locked into either pure material innovation or numerical analysis, this research provides a holistic view of bringing together styling, structural integrity, manufacturability and user-centric performance in a one-off replicable approach.

Future researches may expand this framework by incorporating sustainability inspired materials, digital quality inspection methods and life cycle assessment tools to further improve the environmental performance. The methodology and understanding presented here forms a strong foundation for the development of next-generation automotive interior components with industrial practicality and scalability.

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