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UNIVERSITY OF VAASA

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## **Master's Thesis**

**Reducing Design Iteration Cycles in Design for Additive Manufacturing  
(DfAM) of Components for Hydrofoils & Drones**

School of Technology and Innovations  
Master's thesis in Design for Additive Manufacturing  
Industrial Engineering and Management

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**UNIVERSITY OF VAASA****School of Technology and Innovations**

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**ABSTRACT:**

The purpose of the thesis is to reduce the design iteration cycle time while preserving design constraints and desired functionality, enabling faster product development in high performance applications across industries. The research aims to contribute to the Design phase of Additive Manufacturing (AM) practices for candidate 3D models from industries. The study is motivated by the inefficiency and time consuming nature of the current design process for AM components in specialised applications, which often involves multiple cycles of redesign, simulation, and prototyping that squander precious resources and time.

The Framework of the thesis introduces a general framework to reduce design iteration cycles in Design for Additive Manufacturing (DfAM), which optimises the workpath using a generative design software approach. The framework's architecture is built upon four key pillars: design optimisation, TO, simulation validation, and manufacturing preparation. It integrates multiple specialised software tools for advanced computational modeling.

The research employs a mono-methods approach focused on the practical implementation of a workpath that integrates design, computational modelling with different software, and results evaluation to reduce design iterations and advance DfAM techniques. It adopts a hybrid deductive and inductive research approach to gain in-depth insights into DfAM.

The developed framework demonstrated a considerable reduction in design iterations across all case studies. This significant decrease is attributed to the framework's effectiveness in design refinements and finalisation phases. Despite these advancements, the framework acknowledges limitations such as high computational resource requirements, multi-material limitations, size constraints, and simulation fidelity gaps

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**KEYWORDS:** Additive manufacturing, DfAM, Design iterations, TO, Lattice Integration.

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## Abbreviations

AM	Additive Manufacturing
DfAM	Design for Additive Manufacturing
VR	Virtual Reality
2D	Two Dimensional
3D	Three Dimensional
CAE	Computer Aided Engineering
CAD	Computer Aided Design
TO	Topology Optimization
FEA	Finite Element Analysis
CFD	Computational Fluid Dynamics
BCs	Boundary Conditions
FCC	Face Centered Cubic
BCC	Body Centered Cubic
SLS	Selective Laser Sintering
SLA	Stereolithography
FDM	Fused Deposition Modeling
CMM	Coordinate Measuring Machine
DLP	Digital Light Processing
ERP	Enterprise Resource Planning
STL	Standard Triangle Language
ERP	Enterprise Resource Planning

# 1 Introduction

## 1.1 Motivation for the study

The adoption of Additive Manufacturing (AM) has grown exponentially in many industries, due to its ability to support complex geometries, lightweight structures, and rapid prototyping. Design for Additive Manufacturing (DfAM) is an inventive workflow, offering engineers to collaborate with advanced design methods over traditional and ign methods to generate optimized geometries. The Component development for dynamic products, such as hydrofoils and drones, usually involves the designer undergoing multiple cycles of redesign, simulation, and prototyping to achieve satisfactory performance, and desired functionality. These iterative loops squander precious resources and time for product development across industries.

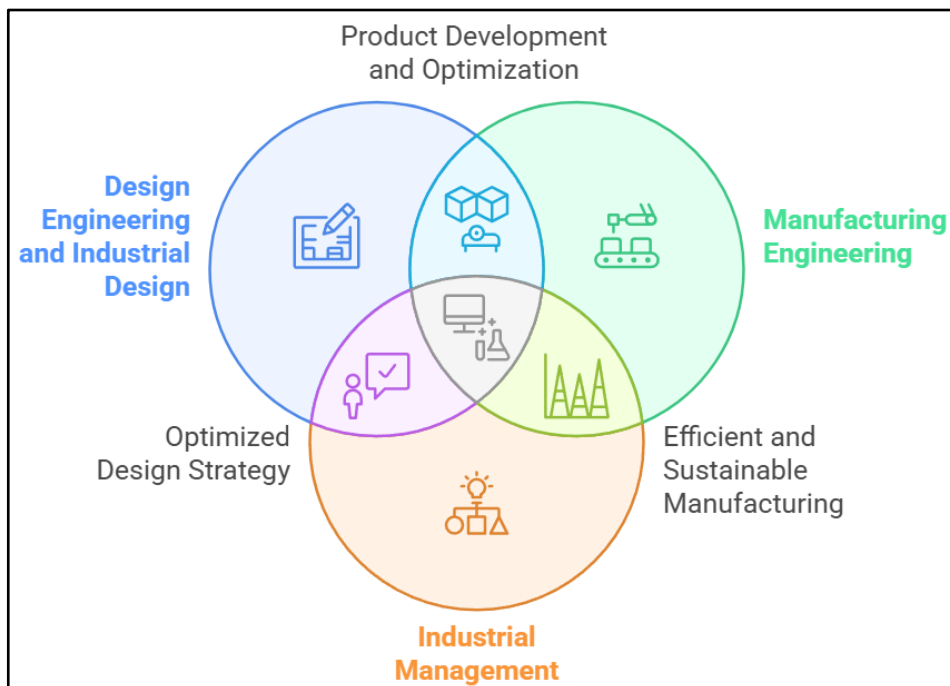
As a mechanical engineer involved in CAD modeling, structural simulation, and manufacturing-inspired design, I have experience in managing the challenges associated with design iterations. I am enthusiastic about hydrofoils, drones, satellite and compliant mechanisms. These components and systems, where weight, precision, hydrodynamics, and aerodynamics functionality are crucial in operation, have drawn me to find ways DfAM methods can be improved to yield results faster and better.

As a student of Industrial Engineering and Management, I am driven by a strong will to bridge the gap between technical design optimization and industrial efficiency. My studies have acquainted me with a multidisciplinary approach, combining engineering design, process improvement, and systems thinking, as a meaningful approach to reduce design iterations in additive manufacturing processes. This thesis is an organic extension of those aims by examining and comparing AM technologies such as Selective Laser Sitering (SLS) and Fused Deposition Modeling (FDM) based on characteristics of fabricated components. By quantifying these results using statistical analysis, this study hopes to offer practical guidelines for engineers curious to optimize DfAM processes.

The prime objective is to reduce number design iteration cycle time while preserving design constraints and desired functionality, to enable faster product development in high-performance applications in across industries.

## 1.2 Field of Science

Contemporary development of industries requires integration of multiple scientific disciplines to address industrial challenges. This research combines four disparate fields of science; Design Engineering and Industrial Design, Manufacturing Engineering, and Industrial Management to define a workflow that converts theoretical potential into practical industrial solutions.



**Figure 1.** Field of science for thesis development *Source: Diagram created using Napkin AI, based on a descriptive prompt (2025).*

Industrial Design and Design Engineering are scientific concepts, encompassing the systematic process of designing products to meet design specifications in terms of aesthetic, ergonomic, and user experience requirements. The field provides the methodological framework for translating user requirements to technical specifications,

establishing design constraints, and optimizing product dynamics. Customer-centric and market orientation of the technical solution are guaranteed by industrial design principles, whereas design engineering methodologies establish the analytical level of intensity for performance testing and reliability.

Manufacturing Engineering bridges the gap between production reality and design intent, focusing on process optimization, quality control, and setting up manufacturing systems. Manufacturing engineering provides technical expertise for converting design specifications into producible products, while preserving production efficiency, cost-effectiveness, and quality assurance. Manufacturing engineering fundamentals focus on material choice, process parameter optimization, and production workflow design in a way that optimizing the mass production of designs.

The integration of these four science domains creates a notable gap in current manufacturing studies, where technological advancements are typically isolated from practical regard for execution. Although each science field has improved significantly, the absence of integrated frameworks inhibits the translation of research into industrial applications. Ideal technical solutions can be created by design engineering that cannot be effectively manufactured by manufacturing engineering, and economic analysis can favor solutions that compromise on design integrity or manufacturing quality.

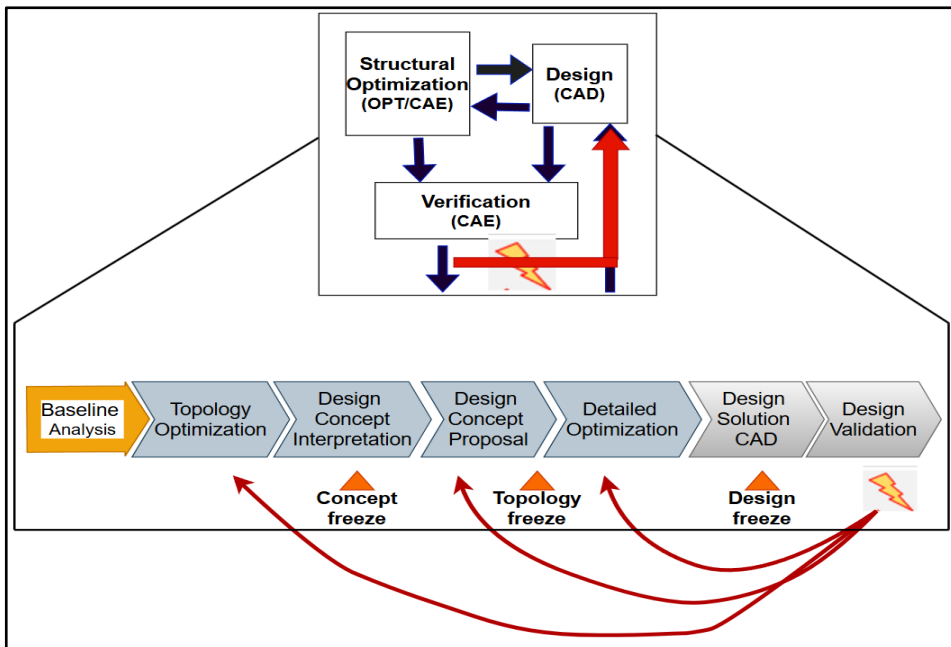
This cross-functional approach provides industrial relevance by encompassing the whole product development process from design concept to manufacturing implementation. Modern manufacturing companies require end-to-end solutions reflecting technical viability, design superiority, manufacturing efficiency, operational coordination, and economic competitiveness simultaneously. By combining design engineering ideology with manufacturing engineering practicality, industrial management and economic justification, my thesis offers an integrated workflow for engineers to practice overcome and barriers and bottlenecks of the existing AM processes.

### **1.3 Additive Manufacturing Workflow**

The thesis research direction mainly integrates Design Engineering, Manufacturing Engineering, and Industrial Management. The transition from traditional CAD to generative design represents a critical technological advancement for additive manufacturing. This computational design transformation directly bonds with the thesis objectives of creating industrially viable AM solutions, fundamentally changing how engineers approach component design and optimization.

Generative design differs significantly from traditional CAD (Computer-Aided Design) approaches, both methodologically and in output. While the CAD relies on manual input, the designer must define the basics of geometries, including design constraints and required features. Additionally, handling CAD depends on expertise in the related field and industry-related experience in generating the desired geometry. The flip of the side generative design leverages algorithms and computational power to automatically generate a wide range of optimized design opportunities, and designers can customize and generate case-sensitive alternatives. Nevertheless, utilizing a generative design approach, the designer must define the design goals, material constraints, manufacturing technology, and performance criteria. In addition, the generative design software explores numerous approaches to meet desired objectives, where it can generate innovative geometries that are often lightweight, lightweight by lattice integration, functionally superior, and tailored for additive manufacturing. Hence, the generative design facilitates defining geometries that would be difficult or time-consuming to achieve manually with traditional CAD tools.

The Additive Manufacturing (AM) has become the technological shift for the manufacturing of complex components across fast-evolving industries such as automotive, marine and aerospace. AM enabling complex designs that were previously impossible to fabricate with conventional manufacturing methods. Despite of these advancements, the design process for AM components, particularly in specialized applications such as automobile engine components, hydrofoils and drones, remains inefficient and time-consuming. The Figure 2Error! Reference source not found. illustrates design process follow up to generate optimized designs practicing design iterations and testing cycles.



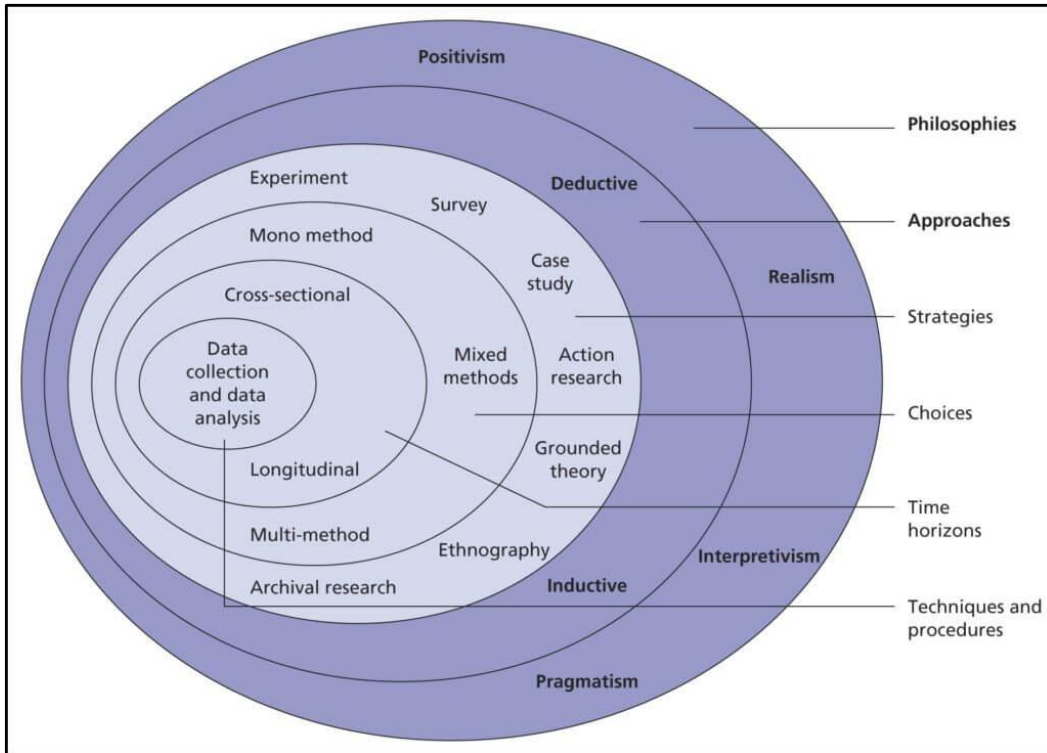
**Figure 2.** Optimization driven design process of AM practicing design iteration and validation.

*Source: Diagram created using diagrams.net (2025).*

In the aerospace and maritime sectors, where progressive research and development involved and the performance is at its best is of such great value, these inefficiencies can represent a major obstacle to hindering to innovation. Automotive engine components are highly complexity embedded with high precision, drone components and hydrofoils require subtle balancing of structural performance. The weight reduction while ensuring the detailed dimension precisness, and aerodynamic or hydrodynamic

performance—attributes that are well suited to AM but also represent very complex design challenges.

#### 1.4 Research Onion Framework



**Figure 3.** Adapted Research Onion for the study *Source: Adapted from Saunders, M., Lewis, P., & Thornhill, A. (2007). Research Methods for Business Students (4th ed.). Pearson Education, visualized with the assistance of ChatGPT, OpenAI, 2025.*

The Research Onion, shown in Figure 3 shows a structured research design model. Six layers of the research are adapted to fit different mixed-methods approaches used to evaluate and compare the characteristics and quality related to technical parameters of three technologies of Additive Manufacturing, namely SLS, FDM, and SLA. Additionally, investigate how does each technology can be used in reducing design iteration cycles using fabricated components.

## **1.5 Research Philosophy – Pragmatism**

The Research Onion framework supports methodological coherence by a step-by-step sequence from philosophical foundations to practical data collection. The pragmatic approach fits to the mixed-methods approach, combining quantitative measures through CAD modeling, simulation analysis, and testing with qualitative insight through design optimization processes and manufacturing workflow observations. This multi-source triangulation approach embraces both the theoretical underpinnings and the practical application requirements, giving balanced coverage of the research objectives without sacrificing scientific validity.

## **1.6 Research approach – Deductive and Inductive**

This study uses a deductive and inductive research approach to achieve insights into the DfAM techniques applied in industrial components from scratch to fully optimal physical prototypes. This combination allows the study to be formulated with the advantages of two types of research methods as theory-driven and experimental-driven research.

In the deductive phase, research assumptions and hypotheses were derived from a comprehensive literature review on a few additive manufacturing technologies, such as SLS, FDM, and SLA. Previous studies assisted in understanding design strategies, performance factors, and issues related to AM technologies. The theoretical motives utilized in deriving detailed assessments on a few technical measures, such as weight optimization, strength-to-weight ratio, dimensional accuracy, surface roughness, and design iteration efficiency.

This was then followed by the inductive phase, which involved making conclusions from the experiential outcomes of the research. CAD models were developed in the VR lab and progressively refined using simulation software, and physical components were fabricated using different AM techniques. Print quality, material usage, experimental observation, and part functionality were tested to identify patterns and relationships not



apparent from the literature. These empirical findings helped to narrow the initial assumptions, validate theoretical models, and enhance the applicability of the research in industrial settings.

By integrating deduction and induction, this study illustrates systematic hypothetical analysis with empirical verification to produce a balanced methodology that enhances the applicability of the findings.

### **1.6.1 Research Strategy**

The research strategy for this study is based on the Research Onion Framework (Saunders et al., 2007), ensuring a structured and logical progression from philosophical stance to data collection techniques. A mono-method approach was adopted to implement the research work focusing on a few case studies, and it's being single, consistent line of analysis on experimental evaluations. This approach supports clarity and depth of the research direction in the context of optimizing design for additive manufacturing (DfAM) in satellite structural components, hydrofoil, and drone parts.

The strategy began with selecting case studies from prominent sectors, where specific components have been identified as suitable candidates for DfAM redesign. The component selection was based on criteria such as geometric complexity, lightweight potential, and structural importance. The chosen parts underwent topology optimization and lattice structure integration, Flow simulation, FEA and so on, which are known as core of DfAM techniques intended to enhance mechanical performance while reducing material usage.

An important design consideration in this strategy was minimization of overhang during 3D printing, also addressing build orientation, and geometry modifications to improve manufacturability. The redesigned parts were then fabricated using two selected additive manufacturing technologies: SLS and FDM chosen for their capabilities are identical in terms of material specifications, resolution, and cost.

As the final phase of the strategy, printed prototypes must be tested and validated. This is included FEA to measure and evaluate technical parameters such as strength-to-weight ratios, dimensional accuracy, surface roughness and a comparison of efficiency of printing technology in terms of time, material use. These experimental results have been used to conclude about the effectiveness of DfAM techniques, software integration and the feasibility of each AM technology.

This research strategy combines digital modeling, manufacturing, and empirical testing in an integrated loop, reinforcing the core goal of the thesis: to reduce design iteration cycles and enhance the efficiency of DfAM through an experimental approach.

### **1.6.2 Time Horizon – Cross Sectional**

This research was carried out within a cross-sectional time horizon, focusing on a specific period. The experiment and analysis implemented for selected components, starting with data collection, CAD redesign, simulations, follow up with experimental testing and results validation carried out. This time-constrained approach aligns with the practical objectives of a master's thesis while allowing for a detailed evaluation of DfAM techniques within a defined timeframe.

### **1.6.3 Data**

There are two types of data, primary and secondary data were utilized in this study to support design, simulation, and analysis tasks. The primary data consisted of CAD models of an aerofoil and a hydrofoil that were developed based on profile generated individually by the researcher using generative design and topology optimization techniques. The CAD models were developed according to standard criteria (Takuma, n.d., Airfoil Tools, n.d.), based on speed, durability, and some of performance and production requirements. Additionally following Design for Additive Manufacturing (DfAM) principles. The Geometric data, design constraints, FEA, and simulation results of components have been utilized for evaluation.

To broaden the scope of the thesis, an analysis of a satellite structural component has been included as secondary data. The initial CAD model of the satellite structure has been externally provided; subsequently, computational modeling, including TO and lattice integration, has been performed. This combination of internally created and third-party data enabled a diverse and realistic assessment of DfAM methods over a variety of functional areas.

#### **1.6.4 Research gap and justification for the current studies**

Despite significant advancements in generative design methodologies, AM technologies, and bio-inspired compliant mechanisms, several critical gaps remain in understanding how these can be optimally integrated to reduce design iteration cycles for automotive, aerospace, and marine applications where performance-critical designs are highly involved.

- i. **Limited Integration Studies:** While generative design and AM have been individually well-studied, research on their integrated application specifically for iteration reduction in aerospace and marine industries remains limited in exploring. Few studies have been evaluated systematically how different generative design platforms facilitate AM technologies to impact overall development efficiency (Gibson et al., 2021; Laverne et al., 2017). This integration is particularly important given the finding by Hassan and Panchal (2021) that software integration capabilities can reduce design-to-manufacturing translation time by up to 75%.
- ii. **Insufficient Cross-Technology Comparisons:** Detailed comparisons on SLS, FDM, and SLA that consider the entire design-to-testing workflow have not been documented, especially for hydrofoils and drone applications where performance is crucial and multifaceted (Thompson et al., 2020). While Takahashi et al. (2022) and Mendez and Kumar (2023) provided valuable insights for specific components of aerospace and marine applications, broader frameworks for technology comparison are lacking.

- iii. **Incomplete Understanding of Process-Specific Design Constraints:** While general DfAM principles are well-established, technology-specific design constraints and their implementation in generative design platforms remain inconsistently documented, limiting the effectiveness of automated design processes (Yang and Zhao, 2020). This gap is particularly evident in the contradictory findings regarding optimal design constraints for SLA-produced hydrofoils Zhang and Patel (2023) and Oliveira and Rodriguez (2022).
- iv. **Gaps in Multi-Software Workflow Optimization:** Research on optimizing workflows across multiple software platforms (CAD, simulation, generative design, and slicing) is limited, with few studies quantifying the impact of software integration on overall iteration efficiency (Wang et al., 2022). This gap is particularly relevant given Thompson and Wilson's (2023) finding that platform selection can significantly impact design iteration efficiency, to minimizing redundant prototyping would be beneficial in terms of time saving and as a cost-effective approach.
- v. **Limited Validation on Virtual Testing Approaches:** Although simulation-based validation shows promise for iteration reduction, comprehensive validation of its effectiveness compared to physical testing, particularly for hydrodynamic applications, remains insufficient (Jahan and El-Mounayri, 2021). This gap is highlighted by the contrasting findings of Park and Ahmed (2022) and Castillo and Bhatt (2023) regarding the effectiveness of digital twins for different application domains.
- vi. **Insufficient Integration of Bio-inspired Compliant Mechanisms:** While bio-inspired compliant mechanisms have demonstrated significant performance advantages (Rodriguez et al., 2023), research on their integration with generative design methodologies and AM-specific workflows remains limited. Few studies have systematically evaluated how biomimetic principles can be incorporated into generative algorithms to reduce design iterations while improving functional performance (Wang and Igarashi, 2021). This integration is particularly important

given the finding by Matthews and Patel (2023) that biomimetic approaches can reduce component count by 60% while improving system-level performance.

In addition to the experimental analysis using design and printed parts in the VR lab, literature and statistical data analysis performed to justify my effort in terms reducing design iterations and performance validations. Based on research articles, lab tests, and publications data was gathered, analyzed and visualization has been performed under the literature review. Additionally, data was build based on printed parts both plastic and metal in the VR-laboratory, then arranged accordingly and analyzed to understand the behavior of define strategy of the thesis follow up with verifying.

## 1.7 Research Objectives and Research Questions

This research aims to contribute to the Design phase of AM. The Design for Additive Manufacturing (DfAM) practices for satellite structural components, drone and hydrofoil components by addressing the following key objectives:

1. To develop DfAM design guidelines focusing on topology optimization and lattice structure integration, specifically tailored for Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) processes.

To compare and evaluate software tools commonly used in DfAM workflows, such as CAD, simulation, and generative design platforms, based on their capabilities to support efficient and accurate modeling, optimization, and manufacturability for complex components.

2. To identify and apply design validation criteria and rules, ensuring that the optimized designs not only meet manufacturing constraints but also maintain structural integrity and performance requirements for real-world applications.
3. To integrate and test the above guidelines by applying them to selected case studies (e.g., hydrofoil, aerofoil, and satellite components) through simulation, physical prototyping, and performance evaluation.

By creating a more streamlined design-to-manufacture workflow, this research seeks to reduce time-to-market significantly for AM components while improving their performance.

The significance analysis of this research lies in addressing a critical academic and industry gap in current DfAM workflows. While much attention has been given to improving AM hardware, materials, and other infrastructure less focus has been given on optimizing the design process itself. By reducing redundant prototyping within the least possible time and creating iteration cycles that are more efficient with seamless integration of other parties involved, this framework will be enabled.

1. Faster design development cycles for performance-critical components with the help of generative design tools.
2. More optimized designs where topology optimized, lightweight while maintaining structural integrity, and less post-processing that fully leverage AM capabilities
3. Better integration of biomimetic principles in engineering applications pushes boundaries of DfAM creating fully optimized, value added final product.

The innovative approach combines established design methodologies with nature-inspired principles to create a realistic framework for engineers working with complex AM components to generate fully optimal, ready-to-manufacture designs. This intersection of manufacturing technology and biological design principles represents a promising framework in engineering design, especially for applications requiring both structural integrity and functional flexibility.

The current design process for additively manufactured components suffers from several key inefficiencies:

1. Manual redesigns that rely heavily on designer experience rather than systematic optimization process powered by generative design software.
2. Slow validation processes requiring physical prototyping between iterations waste time and increase cost.
3. Fragmented software tools that fail to create a seamless design-to-manufacture workflow.
4. Lack of integration between designing, simulating, manufacturing, and quality assurance
5. Limited integration of advanced design methodologies like generative design, topology optimization and embedding lattice structures.

These inefficiencies create the product design development cycles extensive, increased costs, and often sub-optimal final designs would cause for customer dissatisfaction. For time-sensitive applications in fast growing industries, these delays directly impact market competitiveness and slow down the adoption of new technologies.

The research questions will address the challenges associated with design iterations in additive manufacturing, and investigate how digital tools could be used potentially to streamline the design process. The prime objective is to identify possible strategies to improve speed and quality of design loop and decision making in additively manufactured components. Additionally, to investigate the effectiveness of AM technologies on design iterations to generate fully-optimal components. On top of that, focus on reduce physical prototypes, time, and material saving to make the process more sustainable. Research questions are as follows:

#### *Research Questions*

1. How can design iterations loop to be optimized to improve Design for additive manufacturing (DfAM) process?
2. What are the design specifics for FDM and SLS additive manufacturing technologies when integrating lattices and TO processes?

### **1.8 Ethical consideration – use of AI tools**

In line with transparency and responsible research practice, this research acknowledges the use of artificial intelligence (AI) tools to support in some aspects of the research process. AI tools ChatGPT (OpenAI) and Perplexity AI were utilized at the preliminary stages of idea generation, namely to refine the methodological design and to form the outline of the literature scoping. These tools assisted in formulating relevant research paths, understanding theory principles, and researching terminology in Design for Additive Manufacturing (DfAM).



The Napkin AI was used to generate diagrams by providing customized prompt inputs specific to the title and subtitles. Diagrams generated using this tool were read and enhanced to align with the subject matter to ensure the consistency with the study objectives and representation accuracy.

Importantly, all the outputs produced with AI support were thoroughly critiqued, rewritten, and authenticated to ensure academic integrity. All figures produced using AI tools have been attributed in the thesis to ensure ethical transparency.

This approach complies with sound research practice by recognizing the enabling—but cannot operate independently, role of AI in augmenting the research process, without sacrificing originality, critical reflection, or analytical nuance of the thesis.

## **1.9 Thesis Structure**

The remainder of this thesis is organized as follows: Chapter 2 reviews relevant literature on design for additive manufacturing, topology optimization, lattice structures, and biomimetic design principles. Chapter 3 details the methodology and framework development. Chapter 4 presents design, optimization, simulation, and analysis of case studies focusing on hydrofoil, drone, and several other mechanical components. Chapter 5 discusses the results and implications, and Chapter 6 concludes with insights and recommendations for future research. Chapter 7 concludes my thesis with the conclusion and justify my effort on this research work providing answers for research questions. Reference materials such as research articles, websites, and test papers have been listed under the references chapter.

## 2 Literature Review

Generative design is a new approach to engineering design where algorithms are used to search huge solution spaces subject to given constraints and objectives (Matejka et al., 2018). Recently, pave-the-way development of computational infrastructure has widened the array of these approaches to include not only the naive form of topology optimization, but also the multi-physics-physics problems and manufacturing considerations, which are integrated into the design-phase of design generation itself (Wang et al., 2022). This level of integration is especially beneficial for aero and marine industry applications because performance prioritization and sizing under severe limits of mass and structure are often needed.

Lee and Markforged (2021) demonstrated that process-aware algorithms have been specifically designed to fulfill AM constraints. The ability has been proven by producing drone structural components with a 40% weight reduction while preserving the mechanical performance. The study highlighted the importance of process-aware algorithms, which incorporate process-specific constraints during the generation process rather than post-generation as a validation measure. Based on this approach, Rodriguez and Altair (2022) establish frameworks for inserting fluid dynamic objectives into generative design for hydrofoil applications with a 25% drag reduction compared to conventionally designed analogs. This innovation represents the shift from structural optimization in isolation to multi-physics generative approaches that serve the complex requirements of aerospace and marine components.

### 2.1 Integration of simulation tools with AM workflow

Integration of simulation tools into AM process has been identified as an established technique for reducing physical iterations. Kumar and Ansys (2023) set up workflows that integrated structural, thermal, and fluid dynamic simulations with AM process simulation to accurately predict both the performance of a component and the manufacturing outcome. In their aerospace component work, they demonstrated that

accurately calibrated multi-physics simulations could reduce physical prototyping requirements by as much as 60% by simulating ideas virtually.

For hydrodynamic applications specifically, Zhang et al. (2022) established a simulation framework that linked CFD analysis directly with AM process simulation, enabling accurate prediction of surface roughness effects on hydrofoil performance. Their approach reduced design-to-validation cycles by 45% by identifying printability issues and performance impacts before physical production. This demonstrates a critical advancement over earlier approaches that treated design simulation and manufacturing simulation as separate processes, highlighting the value of integrated simulation workflows for components with complex flow-optimized geometries.

### **2.1.1 Software platforms could integrate for Design-to-Manufacturing workflows**

The evolution of software platforms has significantly impacted iteration efficiency in AM-driven development. Hassan and Panchal (2021) evaluated Autodesk's Fusion 360 and nTopology for marine applications, revealing that software integration capabilities directly influenced iteration cycle time, with fully integrated platforms reducing design-to-manufacturing translation time by up to 75% compared to disconnected software workflows.

Siemens NX and Altair Inspire represent alternative approaches to integrated workflows, with distinct strengths in different application domains. Thompson and Wilson (2023) conducted comparative analyses of these platforms for drone component design, finding that Altair's emphasis on manufacturing constraints produced more consistently printable results, while Siemens offered superior integration with mechanical simulation tools. Their work highlighted the importance of platform selection based on specific project requirements and team expertise, demonstrating that software platform choice can significantly impact design iteration efficiency even before physical production begins.

## **2.2 Additive Manufacturing Technologies: Capabilities and Constraints for Aerospace and Marine applications**

Additive Manufacturing is a group of technologies that create objects by adding material layer by layer based on pre-prepared digital models. Unlike traditional subtractive manufacturing, which takes away material from a solid block. AM enables the production of complex geometries with reduced material waste and process time. AM technologies have been significantly improved, and various processes are created for particular applications and materials. A few of the most popular methods are FDM, SLS, and SLA. The methods differ in terms of printing mechanisms, material usage, accuracy, surface finish, and so on. Additive manufacturing has found numerous applications across aerospace, automotive, healthcare, and many consumer products and has emerged as a reliable technology today.

### **2.2.1 Selective Laser Sintering (SLS): Capabilities and Limitations**

SLS method uses high-power lasers to selectively fuse polymer powder layer by layer, offering higher precision for complex geometries and functionally critical parts (Wohlers & Gornet, 2016[9]). Recent developments in the SLS technology have been updated material choice and process control, with systems today achieving higher accuracy in dimension tolerances up to  $\pm 0.1\text{mm}$  while offering isotropic mechanical properties (Chen and Rodriguez, 2022). This isotropy is a principal advantage over alternative AM technologies for parts which has complex geometries and are subjected to multi-directional loads.

For aerospace, Martinez et al. (2023) subjected SLS-produced drone components to dynamic loading and discovered them to be of structural integrity equal to that of injection-molded counterparts but with weight reductions of 30-35% through lattice internal structures. Manufacturing a product without support structures is a significant achievement, since it would minimize the post-processing and would be advantageous in manufacturing components with complex internal geometries. In marine use, Williams and Park (2022) have conducted water tunnel testing of SLS-produced hydrofoil

sections and found that surface roughness could be optimized to maintain 95% of theoretical hydrodynamic performance with optimized process parameters. Their work established SLS particularly suitable for functional prototyping of hydrofoils due to its mechanical properties and geometric freedom, though finishing the surface remained an optimization area. This is a major improvement over earlier SLS implementations, where surface roughness significantly degraded hydrodynamic performance.

### **2.2.2 Fused Deposition Modeling (FDM): Capabilities and Limitations**

The FDM method is well known as the most accessible AM technology due to its lower cost and simplicity in operation (Ngo et al., 2018). The layer-by-layer deposition of thermoplastic materials creates inherent anisotropy in mechanical properties, and the limitation has been documented properly by Wong and Hernandez (2019). Recent developments in advanced materials have expanded FDM's application range, with carbon fiber and high-temperature polymers showing specific performance in manufacturing functional components.

For drone application, Wilson et al. (2021) critically evaluated FDM for structural components, identifying optimal print parameters for maximum strength-to-weight ratios with carbon fiber-reinforced composites. It demonstrated that properly optimized FDM components could achieve 70% of the injection-molded equivalents' strength while enabling rapid iteration cycles for verification of design. This is a significant enhancement from earlier FDM implementations, which typically achieved just 40-50% of injection-molded strength properties.

For naval applications, FDM suffers from surface finish and water absorption issues. Hernandez and Chen (2023) investigated the surface treatments of FDM-processed hydrofoil components and found that acetone vapor smoothing followed by hydrophobic coating has been able to improve hydrodynamic performance and durability. Their study has also highlighted the limitations of FDM in achieving high-performance hydrodynamics, particularly water exposure stability in the long term. Further, the

observation of Williams and Park (2022) concerning SLS suggests that material-specific post-processing problems are a requirement for hydrodynamic components.

### **2.2.3 Stereolithography (SLA): Capabilities and Limitations**

The SLA is an advanced method in additive manufacturing that has been significantly enhanced by digital light processing (DLP) and continuous liquid interface production (CLIP) versions (Ligon et al., 2017). The present systems offer good surface finish and detail resolution, which is reported by Chohan and Singh (2023) as being as low as 25 $\mu$ m, which makes SLA very useful for components requiring high geometric precision.

As a comparison between manufacturing technologies using aerospace applications, Lee and Wang (2022) evaluated SLA for the production of complex drone propeller geometries. Finalizing the evaluation, the improved surface finish directly equated to improved aerodynamic efficiency compared to FDM counterparts. Their research concluded that SLA-produced propellers achieved 95% of the efficiency of conventional manufacturing techniques while allowing for the rapid iteration of complex blade geometries. This high efficiency was in direct comparison to FDM-produced propellers, which achieved only 80-85% efficiency on average due to surface flaws.

For hydrofoil use, SLA offers benefits in surface finish but is challenging in material properties, where Zhang and Patel (2023) conducted detailed evaluations of SLA resins for hydrofoil prototyping. Summarizing their work, while initial hydrodynamic performance was improved due to excellent surface finish, material degradation upon exposure to water for long periods limited functional test duration. They highlighted the importance of resin selection and post-curing operations for marine applications, demonstrating that in some cases, SLA's high surface finish had to be sub-optimized against material durability considerations.

#### **2.2.4 Strategies for reducing design iterations in Aerospace and Marine Industries.**

In aerospace and marine uses, minimizing design iterations is critical for accelerated development cycles, cost savings, and improved time-to-market. Among some of the key strategies are adopting Design for Additive Manufacturing (DfAM) principles that enable engineers to design components for performance as well as manufacturability from the start. Generative design and topology optimization tools are gaining increasing traction for driving the adoption of design refinement as a function of performance requirements. In addition, simulation-based design and digital twin technology provide real-time validation and cycle minimization before actual prototyping. These strategies are particularly useful in managing the complexity of high-performance, lightweight components used in both industries.

#### **2.2.5 Digital Twin approaches to Virtual Validations**

The Digital twin strategies, which maintain synchronized digital and physical representations of components, have also been demonstrated the possibility to reduce the number of iterations in design phase. Park and Ahmed (2022) developed a comprehensive digital twin framework for additive manufactured drone components that employed real-time test data to refine simulation parameters. Their framework reduced physical iterations by 60% through continuous updating of virtual models, enabling the high-accuracy prediction of design changes without physical realization. For marine applications, Castillo and Bhatt (2023) utilized digital twins for hydrofoil design that integrated hydrodynamic simulation, manufacturing process simulation, and physical test data. Their platform enabled simultaneous optimization of performance and manufacturability and led to a 35% reduction in overall development cycles and a 15% improvement in the final component's performance compared to conventional methods. These improvements are significant for marine applications because of the complex interaction between surface quality, material properties, multidirectional stress, and hydrodynamic performance.

The application of digital twins represents a major enhancement compared to traditional simulation-based approaches, as noted by Kumar and Ansys (2023), who described that while standard simulations provide beneficial predictive capability, digital twins enable the continuous enhancement of prediction accuracy obtained by feedback loops between physical testing and virtual models.

### **2.2.6 Parametric optimization and Design space exploration**

The Parametric optimization techniques have been particularly promising in reducing iteration cycles for performance-critical applications. Nguyen et al. (2022) developed a parametric hydrofoil design system integrated with CFD analysis and AM constraints that automated the translation of hydrodynamic performance requirements into printable geometries. Their process reduced design-to-test cycles from weeks to days by enabling the fast exploration of design spaces constrained by both performance requirements and manufacturing constraints.

For aerospace applications, Kim and Johnson (2022) employed a multi-objective optimization framework on drone structural components that simultaneously considered aerodynamic performance, structural integrity, and AM printability. Their approach reduced design iterations by 40% while improving component performance by systematically searching the constrained design space. This multi-objective approach is a significant advancement over earlier single-objective optimization methods as it addresses the complex interplay between performance requirements and fabrication constraints characteristic of aerospace applications.

The success of parametric approaches appears highly dependent on the quality of constraint definition, as noted by Rodriguez and Altair (2022), who found that ill-defined manufacturing constraints could lead to technically optimal but practically unmanufacturable designs, and stressed the importance of manufacturing experience in formulating constraints.



### **2.2.7 Process parameter optimization Iteration reduction**

The Process parameter optimization is now a key method for reducing iterations by improving first-time success rates. Velasco and Thompson (2023) developed machine learning algorithms to predict optimum process parameters for SLS production of thin-walled drone components, reducing print failures by 55% and post-processing requirements by 40%. Their approach utilized historical production data to develop correlations between part geometry, material properties, and optimum process settings, it is a kind of running an algorithm for design optimization.

For marine applications for SLA, Oliveira and Rodriguez (2022) introduced a comprehensive parameter optimization system specifically for hydrofoil parts, balancing surface finish requirements against mechanical performance. Their research demonstrated that optimized parameters could reduce post-processing requirements by 65% and improve part consistency while reducing iteration time significantly. Their findings are in direct contradiction to earlier research by Zhang and Patel (2023), who had speculated that post-processing requirements for SLA-fabricated hydrofoils were largely unavoidable, citing the rapid rate of process optimization technique development. The use of machine learning methods for parameter tuning is a significant advance on traditional design of experiments (DOE) methods, Chen and Rodriguez (2022) assert, having found that ML-based methods were capable of identifying non-obvious sets of parameters that traditional DOE methods are unlikely to catch up.

## **2.3 Comparative studies of AM technologies for Aerospace and Marine Applications**

In considering AM methods SLS, FDM, and SLA have been chosen for specific applications, and certain applications have made good recommendations to choose the correct technology based on the requirement. Takahashi et al. (2022) carried out thorough analyses of SLS, FDM, and SLA for thin-walled aerodynamic components, not only

looking at the ultimate performance of the component but also the overall product development time, cost, and iteration efficiency. They built quantitative choice systems depending on the component specifications and development stage to determine the technology that could affect overall development time up to 60%.

For hydrofoils, Mendez and Kumar (2023) performed comparative analyses by the same criteria but with a specific framework placed on hydrodynamic performance and iteration efficiency. They ensure that although SLA produced parts with better initial surface quality, SLS could produce parts with greater overall quality. For the comparison of technologies SLA and SLS, several parameters such as the entire development cycle, post-processing requirements, and greater stability in test conditions have been considered.

Both studies concluded that every technology has its own inherent characteristics, and no single technology did well on all the measures, a result that implies optimal technology choice consists of a close examination of specific application requirements and development priorities. This emphasizes the importance of comparative processes that combine technical and practical concerns

### **2.3.1 Iteration efficiency across development phases**

The relationship between choosing the correct technology and iteration performance varies significantly across development phases. Zhang and Morales (2022) tracked iteration cycles of drone components from initial preparation and planning to final output, and they found that optimal technology selection varied as development progressed. Their results have shown FDM to be more efficient in conceptual design phases (saving iteration time by 65%), and SLS was optimal in functional test phases (reducing iterations by 40%).

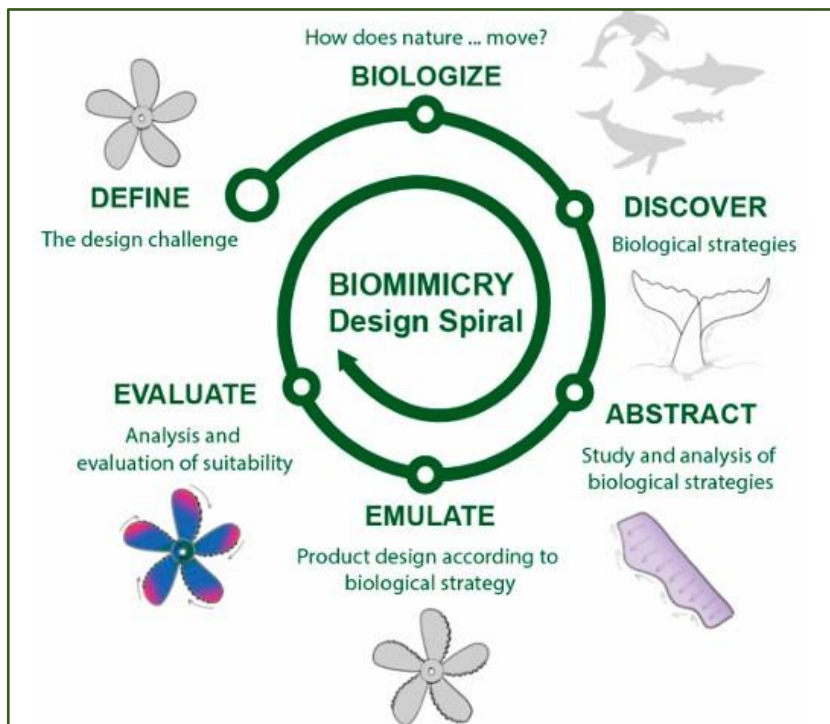
For hydrofoil development, Castillo et al. (2023) identified matching phase-specific strengths, where FDM was best suited to early concept validation and SLA delivered strength in detail design phases where hydrodynamic performance was most important. Their work indicated potential strengths of multi-technology strategies shifting between platforms as development progresses. Phase-specific strategy differs from earlier work testing technologies in silos, giving a more nuanced understanding of technology selection throughout development.

Both findings of the aerospace and marine applications show remarkable similarity in technology phase-specific advantages, regardless of the diversified performance requirements of these applications. This suggests that development-phase concerns can be equally important as application-specific needs in selecting AM technologies, a notion not accepted in earlier literature.

## **2.4 Bio Mimicking Compliant Mechanisms**

The Bio-inspired design has become a powerful paradigm that uses nature's inheritance systems and structures as the source of inspiration to address complex engineering challenges (Shu et al., 2011). Compliant mechanisms, which achieve motion through elastic deflection of compliant members rather than traditional rigid-body joints, constitute a leading field of application of biomimetic principles (Howell et al., 2013). Compliant biomimetic mechanisms have been found to yield major advantages in aerospace and marine applications, since their key features, such as mechanical simplicity, weight reduction, and performance efficiency, etc.

Nature-inspired biomimetic designs have become increasingly prevalent in industrial applications due to their inherent durability and easy adaption to different operating conditions creating a revolutionary movement in modern engineering. The Deployment of biomimetic design is a formal process through a functional abstraction methodology that, in a systemic manner. Deconstructs biological systems, maps their function into engineering needs, quantifies the dimensional and performance metrics of interest, and applies scaling techniques that preserve functional principles while spanning the needs of industries. The Figure 4 illustrates innovations can be initiated from pure nature structures, and perform an analysis follow up with evaluation to define a solution address existing challenges in industries which would offer more natural facet.



**Figure 4.** Innovation inspiration and abstraction by nature *Reprinted from "Innovation Inspired by Nature: Applications of Biomimicry in Engineering Design," by T. A. Planet & E. Peralta, 2024, University of Sville. Copyright 2024 by the authors. Reproduced with permission.*

Martínez-Frutos and Herrero-Pérez (2018) demonstrated that biomimetic compliant morphologies based on avian wing shape could lead to up to 30% improved aerodynamic

performance compared to the traditional rigid control surfaces in the case of drones. Their computational approach utilized generative design procedures combined with bio-inspired motifs for generating adaptive wing morphologies that dynamically changed shape depending on flow conditions. Similarly, Chen et al. (2022) designed compliant propulsion mechanisms for underwater vehicles inspired by fish caudal fin locomotion and showed 25% efficiency improvement in energy compared to conventional propellers and significantly reduced mechanical complexity and failure points.

The union of generative design with biomimetic thinking is a very promising direction of research. Wang and Igarashi (2021) termed computational frameworks exploiting biological motion patterns as functional goals within generative algorithms to enable automated compliant mechanism design mimicking specific natural movement. In applying their research about drone components bio-inspired by wing movements of birds, they showed that bio-inspiration-based generative methods can produce designs that are 45% better in performance-to-weight ratio compared with conventional topology optimization.

#### **2.4.1 Design and actuation of a biomimetic Beetle wing**

The paper "Mimicking unfolding motion of a beetle hind wing" by Muhammad et al. (2009) presents experimental research that has focused on creating an artificial hind wing that replicates the unfolding motion of the *Allomyrina dichotoma* beetle. Inspired by insect flight principles, particularly the foldable wing mechanism of this large beetle, the study aims to provide insight for portable nano/micro air vehicles (MAVs) with morphing wings.

Based on the working principle of the beetle's wing, observed, two types of artificial foldable wing models have been devised: one based on the out-of-plane mechanism described in existing literature, and a second designed to mimic the observed in-plane unfolding motion. The in-plane model has been designed to replicate specific parts of the real wing, such as veins, membrane, bending zone, marginal joint, and medial bridge.

Both artificial wing models have successfully demonstrated the ability to unfold using shape memory alloy (SMA) wires as artificial muscle actuators. The SMA wires provide the necessary force and deformation when heated by electric power. The paper illustrates that the artificial in-plane wing model more closely mimics the real beetle wing's unfolding mechanism compared to the out-of-plane model. This research contributes to the understanding and replication of complex biological mechanisms for potential application in biomimetic engineering, particularly for morphing wings in MAVs.

The Figure 5 shows the aforesaid beetle's wing developed in a CAD software according to the research paper describes and embedding required accessories could develop it for advance engineering applications.



**Figure 5.** Biomimetic Beetle wing modeled in Onshape *Source: Muhammad, A., Park, H. C., Hwang, D. Y., Byun, D., & Goo, N. S. (2009). Mimicking unfolding motion of a beetle hind wing. Chinese Science Bulletin, 54(14), 2416–2424. <https://doi.org/10.1007/s11434-009-0242-z>*

From an additive manufacturing perspective, this approach has reshaped and simplified the complexity in designing and manufacturing. AM technologies by themselves can design and simulate in a minimum number of iterations using this type of biomimicking mechanism. The fabrication of intricate biomimetic structures are impossible with conventional manufacturing methods, but using AM assist in manufacturing this type of functional components while preserving their functionality. Additionally, in the case of

compliant mechanisms in particular, additive manufacturing allows for unprecedented liberty for engineers to design meticulous, monolithic parts with integrated flexible joints, controllable material properties, and complex inner geometries.

Additionally, this approach is followed by further strength from a holistic compliant mechanism design that provides engineers a parametrized joint topology library for different requirements of motion. AM supports material selection methodologies depending on fatigue lifetime and elastic response characteristics. The big deformation analysis algorithms help for reliable behavior prediction of compliant mechanisms, and manufacturing restrictions that refine designs into additive manufacturing potential.

#### **2.4.2 Additive manufacturing braces for Biomimetic compliant mechanisms**

Additive manufacturing has proved to be an ideal manufacturing technology for biomimetic compliant mechanisms because natural structures tend to have complex geometries that are impossible to fabricate using conventional manufacturing techniques (Li et al., 2022). The layer-by-layer construction of AM enables complex compliant mechanisms to be fabricated with precisely controlled material distribution and mechanical properties.

Kumar and Reddy (2023) provided in-depth evaluations of AM technologies for the creation of biomimetic compliant mechanisms from insect wing structures. Their research demonstrated that SLA was extremely well-suited for the creation of fine-featured compliant hinges with controlled flexibility, having motion ranges within 5% of their biological equivalents. SLS, on the other hand, was determined to be useful for larger-scale compliant mechanisms that required isotropic mechanical properties, such as adaptive wing structures found in birds.

For naval applications, Zhang et al. (2023) investigated the production of fish-inspired flexible fin structures using a variety of AM technologies. Their study showed that multi-material PolyJet printing offered particular advantages for emulating the graduated stiffness profiles of natural fins, enabling more efficient propulsion systems for underwater vehicles. This graduated flexibility, difficult to achieve with traditional

fabrication techniques, resulted in 35% efficiency improvements in hydrodynamic performance compared to stiff fin designs.

### **2.4.3 Design to Manufacturing approaches for Biomimetic Mechanisms**

These successful biomimetic compliant mechanisms also require design-to-manufacture integration, along with ideas to consider both biological motivation and manufacturing constraints simultaneously. Patel and Johnson (2022) created frameworks for translating biology principles into manufacturability-constrained designs and demonstrated how simultaneous integration of AM constraints would reduce iteration cycles by 50% compared to manufacturing validation methods following design.

Liu et al. (2023) developed machine learning models that identified optimal AM process parameters for biomimetic compliant mechanisms based on desired mechanical performance. Their approach applied vast data sets of biological motion patterns and corresponding mechanical structures to predict optimal process settings for specific functional requirements. This data-driven approach reduced design-to-manufacture iteration cycles by 40% but improved functional performance by 25% compared to traditional parameter selection methods.

Simulation tool coupling has particularly benefited biomimetic compliant mechanism design. Hernandez and Thompson (2022) established multi-physics simulation environments optimized for flexible structures, enabling accurate prediction of mechanical performance as well as results from manufacturing. Their experiments on bird-inspired drone wings demonstrated that accurately tuned simulations were able to reduce physical prototyping requirements by 65% by accurately predicting complex deformation behavior before physical manufacture.



## 2.5 Comparative Study of Additive Manufacturing Methods

A combination of published research data and experimental results have been used in conducting a comparative study of selective laser sintering (SLS), fused deposition modeling (FDM), and stereolithography (SLA) technologies. Some of the key performance measures were print time, dimensional accuracy, surface roughness, mechanical strength, and cost.

According to search results (Formlab comparison), a key metric has been defined to evaluate the performance of each technology as described; print time, surface roughness, dimensional accuracy, material costs, and design limitations (e.g. minimum wall thickness).

**Table 1.** AM technologies Performance Matrics

Technology	Print Speed (Controller)	Surface Roughness (Ra)	Dimensional Accuracy	Cost (Material)
FDM	10h 32m (1 assembly)	25.3 $\mu\text{m}$	$\pm 0.15$ mm	\$50 - \$150/kg
SLA	2h 36m	6.8 $\mu\text{m}$	$\pm 0.02$ mm	\$100 - 200/L
SLS	3h 52m	12.5 $\mu\text{m}$	$\pm 0.05$ mm	\$100/kg

The Table 1. AM technologies Performance Matrics shows the values with respect to each parameter measured in terms of performance of each 3D printing method. For instance, it is observed that SLA tends to have the highest dimensional accuracy ( $\pm 0.02$  mm) and least surface roughness (6.8  $\mu\text{m}$  Ra), while FDM tends to have higher print speeds and lower material cost but at the expense of surface roughness (25.3  $\mu\text{m}$  Ra) and accuracy ( $\pm 0.15$  mm). SLS provides a compromise with medium accuracy ( $\pm 0.05$  mm), surface roughness (12.5  $\mu\text{m}$  Ra), and average material cost.

## 2.6 FDM Surface roughness evaluation

The FDM is considered as allow cost printing method and much economical for low dimation accuracy and high tolerance components. The subjected study has been conducted with PLA-Aluminum filament material having focused on enhance the surface

roughness, since layer thickness and raster angle affect surface roughness as illustrated in the Table 2. FDM surface quality evaluation

**Table 2.** FDM surface quality evaluation

Layer Thickness (mm)	Raster Angle ( $\hat{A}^\circ$ )	Surface Roughness (Ra, $\hat{A}\mu\text{m}$ )
0.1	0	10.2
0.2	45	15.8
0.3	90	20.5

Experimental test data referred to several resources, such as Formlabs (2024), Xometry Pro (2023), and scientific research articles. The test data referred to test samples, including drone wing fragments and hydrofoils, have been printed using each technology. The dimensional accuracy has been measured using calipers or a Coordinate Measuring Machine (CMM), and surface roughness has been recorded using specific equipment. Mechanical properties as shown in the Table 3. Mechanical Properties, i.e., tensile strength, have been tested following standard test methods. The costs as shown in the Table 4. Material cost involved were material and machine time, and complied with manufacturer recommendations and industry magazines.

**Table 3.** Mechanical Properties

Technology	Tensile Strength (MPa)
FDM	32-55
SLA	55-85
SLS	48-58

**Table 4.** Material cost

Technology	Material Cost
FDM	\$50 - \$150/kg
SLA	\$100 - \$200/L
SLS	\$100/kg

## 2.7 Statistical Analysis for AM technologies comparison

Based on data gathered, a statistical analysis was performed to visualize a comparison between three vital technologies in additive manufacturing; SLS, SLA, and FDM. The data has been accumulated from research articles based on criteria shown in the Table 5. Quantitative metrics to collect data, from journals and lab tests to etc.

**Table 5.** Quantitative metrics to collect data

Metric	Definition	Tools/Instruments
1. Dimensional Accuracy	Deviation from CAD model (mm)	Calipers, CMM
2. Surface Roughness	Ra ( $\mu\text{m}$ )	Alicona InfiniteFocusSL
3. Tensile Strength	Maximum stress before failure (MPa)	Universal Testing Machine
4. Print Time	Total time per part (hours)	Printer software
Cost	Material + machine time (USD)	Manufacturer quotes

The statistical analysis has been performed using python 3.12 in a Windows 11 computer, and certain libraries such as Pandas, Numpy, Seaborn and Scipy were used to analyse data in the Visual Studio workbench. The code snippets has been inserted in the content for the explanation on analysis.

### 2.7.1 Analysis in Python

The analysis is started with importing libraries, followed by load data and derive Descriptive statistics, relevant code snippets are in the appendices, and the derived statistical parameters are shown in the Table 6.

**Table 6.** Descriptive statistics

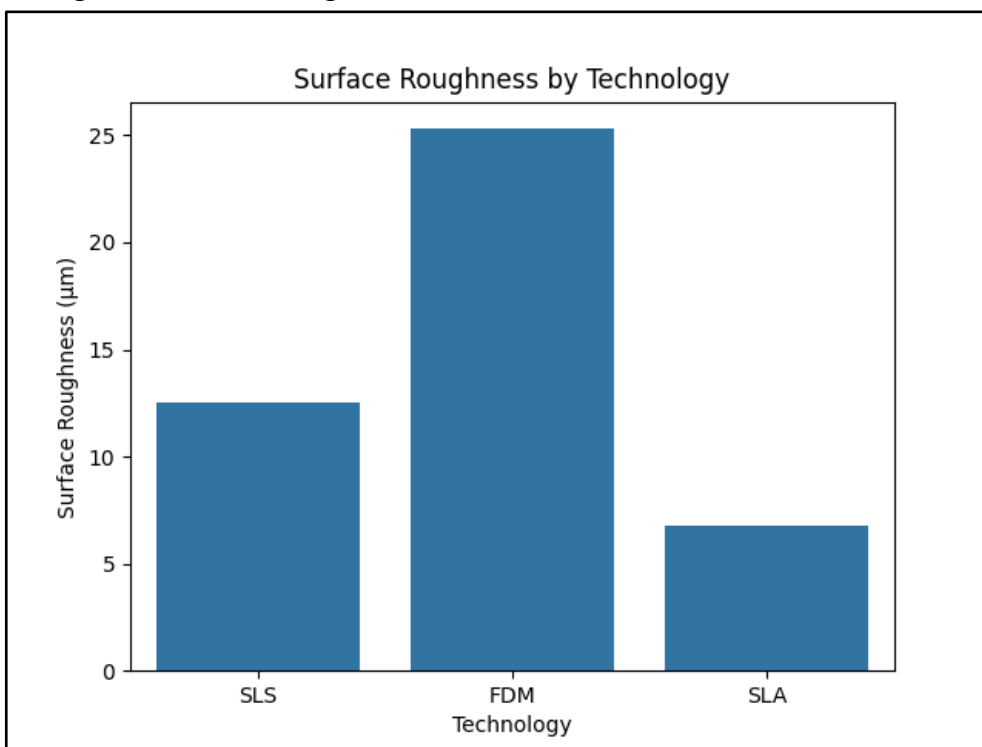
```

1 | | | Print_Time | Dimensional_Error | ... | Tensile Strength | Cost
2 | count | 3.0 | 3.000000 | ... | 3.000000 | 3.000000
3 | mean | 90.0 | 0.073333 | ... | 45.000000 | 46.666667
4 | std | 30.0 | 0.068069 | ... | 11.789826 | 25.166115
5 | min | 60.0 | 0.020000 | ... | 32.000000 | 20.000000
6 | 25% | 75.0 | 0.035000 | ... | 40.000000 | 35.000000
7 | 50% | 90.0 | 0.050000 | ... | 48.000000 | 50.000000
8 | 75% | 105.0 | 0.100000 | ... | 51.500000 | 60.000000
9 | max | 120.0 | 0.150000 | ... | 55.000000 | 70.000000
10 |
11 | [8 rows x 5 columns]
```

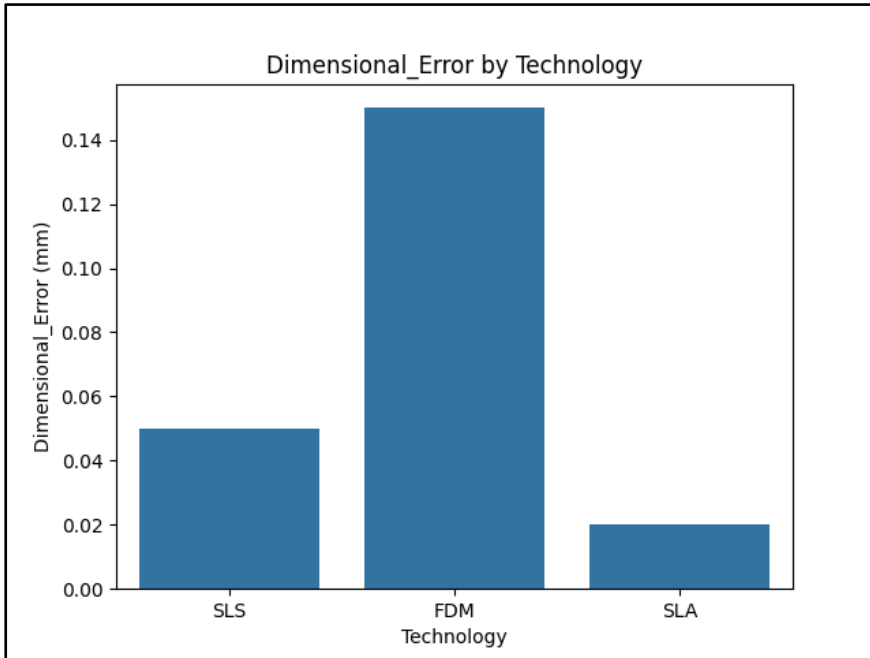
As the shows, several statistical parameters can be seen with respect to the data accumulated.

### 2.7.2 Plots generation

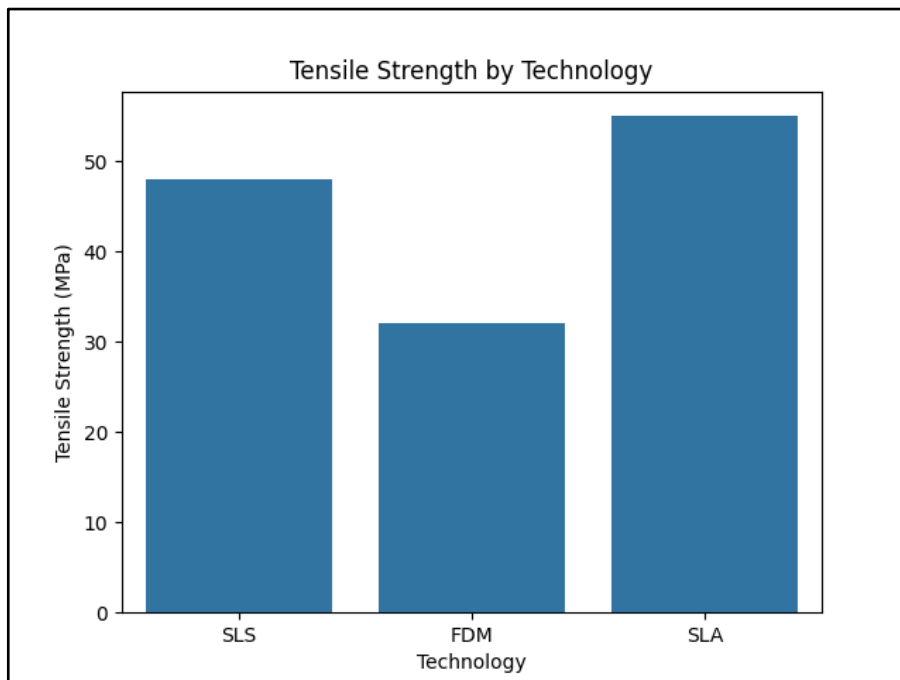
Each technical parameter has been obtained from the data, has been analyzed using Python and plots have been generated for Surface roughness, Dimensional error, and Tensile strength have been described their variation in Figure 6. Surface roughness of AM technologies, Figure 7. Dimensional Error of AM technologies, Figure 8. Tensile Strength of AM technologies



**Figure 6.** Surface roughness of AM technologies



**Figure 7.** Dimensional Error of AM technologies



**Figure 8.** Tensile Strength of AM technologies

Each plot elaborates the distinguishingness of AM technologies, and no single technology is good at every three technical parameters, Selective Laser Sintering can be identified as a moderate option over others. Nevertheless, engineers must take into design consideration, must choose the printing technology wisely fulfilling necessary constraints to manufacture parts with right technology.

### **2.7.3 Efficiency/ Performance advantages of Biomimetic Compliant Mechanisms**

The Biomimetic compliant mechanisms have demonstrated significant performance improvements in diverse uses in aerospace and marine applications. Rodriguez et al. (2023) conducted a detailed comparison of conventional and biomimetic drone control surfaces and concluded that bio-inspired compliant mechanisms achieved weight reductions of 40% while increasing aerodynamic efficiency by 25% through adaptive shape changes in flight. These improvements were directly attributed to longer flight times and maneuverability during outdoor experiments.

For application on submarines, Wang and Chen (2022) compared fish-based propulsion systems to conventional propeller systems on several performance metrics. Their study revealed that biomimetic compliant fin systems performed 30% more propulsive efficiency at low speeds, and the noise was significantly reduced. Reduced mechanical complexity in the systems also translated to improved reliability prediction, where the mean time between failures was calculated to be 300% higher than conventional propulsion systems.

The multi-functional nature of biomimetic compliant mechanisms is especially a useful advantage. Matthews and Patel (2023) designed adaptive insect-inspired structures for drones where sensing, actuation, and structural functionalities are embedded into one compliant element. Their systematic methodology eliminated 60% of elements and increased system-level performance through eliminating junctions and minimizing the requirements of assembly. This multifunctionality, enabled by both aspects of biomimetic design and the capabilities of AM production, is considerably more than any achieved through conventional systems based on individual components.

### **3 Methodology**

The previous chapter outlined literature pertinent to the understanding of the research topic as well as assisting in designing the right questions to be used in the Methodology. Within this chapter, the research methodology that was used to reach the thesis goals is outlined. This chapter outlines the philosophical assumptions, research strategy, methodological design, data collection techniques, and analytical tools used within the study. The research methodology is structured using the Research Onion model (Saunders et al., 2007), which allows systematic research development from the philosophical to technical execution.

#### **3.1 Methodological Choice**

This research utilizes a mono-methods approach of unique practical implementation of work path consists design, computational modeling with different software integration, results evaluation while reducing design iterations. Additionally, provide insight for the advancement of DfAM techniques. The methodology focuses on defining a workpath that reduces additive manufacturing's design iteration cycles for performance-critical components in aerospace, and marine industries adding values with biomimetic compliant mechanisms. The methodology includes the practical implementation constraints to define solutions that are scientifically sound and industry-viable.

#### **3.2 Case study/ Use case selection**

The thesis has a practical approach to generate the research output, since the study commenced by selecting suitable components/ applications from relevant industries. The criteria considered on selecting components were; possibility for weight reduction, TO, and performance evaluation. The hydrofoil and aerofoil were modeled from the scratch, while a satellite structure was selected as a use case with a pre modeled CAD. Once the CAD are bases are ready, computational modeling was performed and analysis for the evaluation.

During the process, data was gathered focusing on statistical analysis to deepen the research approach with data analysis.

### **3.3 Design/ Redesign process**

The design phase involves DfAM techniques using different CAD software, depending on infrastructure, designer familiarity, geometry constraints; preferred software can be chosen, including Onshape, Solidworks, and NX etc. The TO is employed as a key technique to reduce unnecessary mass without compromising the overall strength. At the same time, lattice structures were implemented to maximize the strength-to-weight ratio while maximizing the material distribution. Functionally graded designs were also explored to optimize performance parameters across different areas of the component. Minimization techniques of support were also employed to ensure that the designs are economical and efficient to print, particularly for FDM and SLS technologies.

#### **3.3.1 Design for Additive Manufacturing Integration**

The integration of Design for Additive Manufacturing (DfAM) principles was a core methodological element in this study. This involved embedding guidelines using generative design software tools and applying process-specific requirements related to additive processes, such as FDM and SLS, to optimize part performance and manufacturability. The designs have been modified using DfAM techniques, such as topology optimization, internal lattice structures, and minimal support requirements, to ensure better material utilization, lightweighting, and process efficiency. The CAD models have been iteratively evaluated against DfAM rules to align with AM-specific constraints and capabilities to ensure a seamless transition from digital model to physical prototype.

#### **3.3.2 Software Integration**

The methodology with the integration of DfAM utilizes multiple specialized software platforms, each serving distinct functions in the design-to-manufacture workflow:



- **Solidworks/Onshape:** Used for basic CAD modeling, assembling and biomimetic compliant mechanism development.
- **Altair Inspire:** Applied for topology optimization, lattice integration and structural analysis.
- **nTopology:** Utilized for advanced lattice generation and integration into optimized structural forms.
- **Python/ Excell:** Utilized for data arrangements, cleaning, and analysis has been performed.

### **3.4 Simulation and Analysis**

This section describes the simulation techniques have been applied to evaluate and optimize designs developed with DfAM techniques. Upon completion of design/redesign of the components, advanced simulation tools were used to test performance. Finite Element Analysis (FEA) was used to analyze the mechanical response under environments of realistic loadings, and Computational Fluid Dynamics (CFD) was utilized to calculate thermal resistance where applicable. Printability analysis was even performed to guarantee the manufacturability of the designs using selected AM technologies. This allowed design problems to be resolved early on and supported further optimization of geometries for manufacturing in actual environments.

The simulation process exercised in this research was focused on two main areas: The process simulation and structural optimization using multi-scale and multi-material approaches.

#### **3.4.1 Process Simulation for Additive Manufacturing**

Process simulation has been conducted to assess printability and manufacturability before the prototype fabrication. Key simulation metrics included the following criteria:

Overhang Analysis and Support Estimation: Models have been evaluated for overhang regions requiring support structures. The aim was to reduce the use of support material without compromising the structural integrity of the component.

Layer-wise Build Simulation: A detailed simulation of the layer-by-layer fabrication process was performed to identify potential deformation or thermal distortion and deformation issues.

Support Structure Optimization: Based on overhang analysis, optimized support layouts were proposed to minimize post-processing effort while ensuring print stability.

These simulations helped refine the models to align with the practical constraints of SLS and FDM technologies.

### **3.4.2 Multi-Scale and Multi-Material Topology Optimization**

To enhance structural performance, both multi-scale and multi-material design strategies were implemented.

Macro-Scale Topology Optimization: At the macro level, topology optimization was applied to define the overall geometry of the component. This step was aimed at reducing weight while maintaining stiffness and functionality.

Micro-Scale Lattice Design: At the micro level, different lattice structures were embedded within the optimized geometry. The orientation and density of the lattice were tailored to improve local mechanical behavior and reduce material usage.

Multi-Material Implementation: Variable material properties have been introduced by assigning different lattice types or densities in specific regions of the same component offering extensive stiffness and flexibility. Additionally, Based on functional requirements, to enhance the performance of critical applications such as satellite and drone components multi material optimization can be utilized.

These simulation approaches contributed to refining the design for optimal mechanical and manufacturing performance.

### 3.5 Literature/ Statistical based data analysis

In addition to the experimental analysis using design and printed parts in the VR lab, literature and statistical data analysis performed to justify my effort in terms reducing design iterations and performance validations of additive manufacturing technologies. Based on literatures such as research articles, lab tests, and publications data was gathered, analyzed and visualization has been performed under the literature review. Additionally, data was build based on printed parts both plastic and metal in the VR-laboratory, then arranged accordingly and analyzed to understand the behavior of define strategy of the thesis follow up with verifying.

### 3.6 Evaluation Criteria

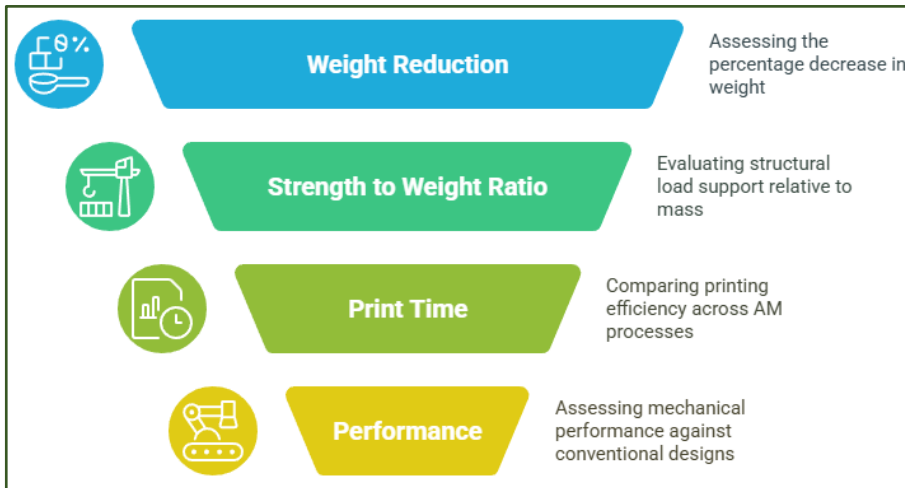
The prime objective of this research to evaluate the effectiveness of DfAM incorporation with generative design software. The relevant criteria have been chosen based on their relevance to both performance and efficiency in the context of additively designed and manufactured components. The components of the evaluation matrices include following criteria:

**Weight reduction (%):** The weight reduction achieved through invented strategy (the percentage decrease in weight) utilizing design optimization, topology optimization compared to a baseline or conventionally manufactured equivalents.

**Strength to Weight Ratio:** A critical parameter in subjected industries, matric is used to asses how does design supports structural loads relative to its mass.

**Print time:** Evaluate the printing efficiency of each components, by comparing the duration for different AM process (for Plastic-FDM and Metal-LPBF).

**Performance:** Implemented to Evaluate and understand the mechanical performance of DfAM-optimized components (e.g., dimensional accuracy, stiffness, load-bearing capacity) against conventionally designed components using simulation and empirical testing data.



**Figure 9.** Evaluation matrices defined to evaluate the performance *Source: Diagram created using Napkin AI, based on a descriptive prompt (2025).*

This evaluation matrices assist for a detailed and quantifiable comparison of AM technologies, while highlighting the practical advantages of utilizing optimized designs in industrial applications.

### 3.7 Experimental Methodology

The experimental methodology employed in this research is to explore and validate the applicability of DfAM techniques for subjected components, satellite structure, hydrofoil and drone components, and biomimetic spring mechanism. Candidate components were strategically chosen due to their critical performance requirements, lightweighting possibilities, and potential for structural optimization in relevant industries. The inherent loading conditions and their potential to benefit from additive manufacturing justified due selection as case studies.

CAD models have been developed using generative design software tools and then further refined through advanced computational modeling with the help of DfAM

techniques. This step aimed at reducing material usage while ensuring mechanical strength and desired performance. The optimization phase also integrated lattice structures where appropriate and emphasized support minimization to align with DfAM best practices. In the additive processes, generative design software tools have been utilized in optimizing geometries for additive processes. Following the design optimization phase, Finite Element Analysis (FEA) was conducted to simulate mechanical behavior under prescribed loading conditions. This simulation evaluates physical parameters such as stress distribution, deformation, and structural integrity to ensure the technical suitability before physical prototyping.

Upon completing simulations, components meet the performance threshold, and the finalized CAD files are prepared for 3D printing using slicing software. This involved exporting models in STL format, orienting them for optimal printing, generating support structures, and slicing using appropriate software tools for each technology. Care was taken to maintain consistency across different technologies to ensure a valid comparison of the outcome.

### **3.7.1 Additive manufacturing prototyping**

To investigate the performance and suitability of different AM technologies, prototypes have been fabricated using two different 3D printing processes: FDM and SLS. These technologies were selected based on their industrial use cases, such as aerospace and marine domains. Each part has been manufactured using the CAD model to ensure consistency and validity in the comparative evaluation.

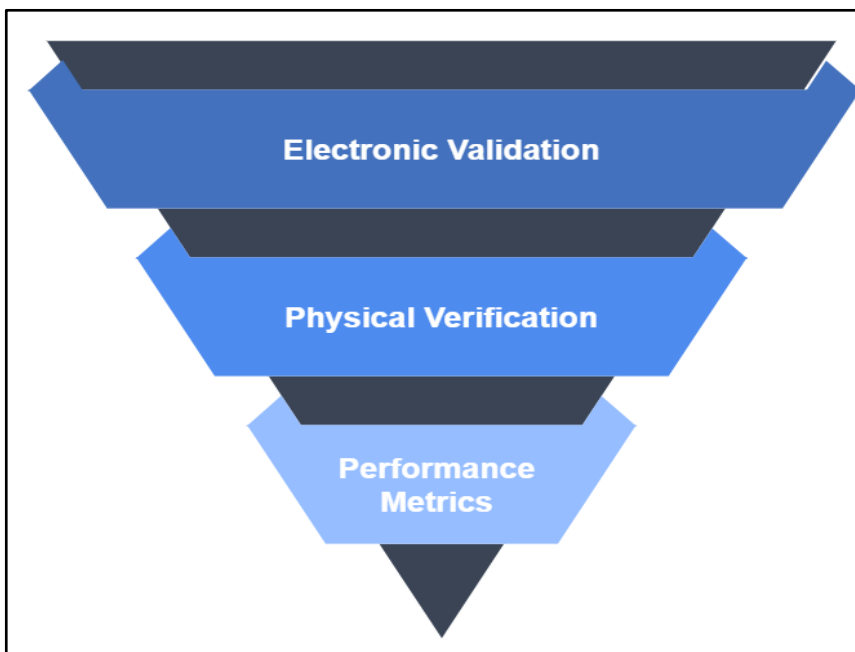
Printing materials with plastic were carried out with FDM using the Ultimaker Cura machine, and the material was PLA. This process offered rapid prototyping at a relatively low cost, although there are some limitations in resolution and mechanical strength. Printing parts with metal, SLS was used in the Prima Additive machine with the material aluminum, making it ideal for performance-critical applications.

To set up the printing, each 3D model underwent a standardized fabrication procedure specifying printing parameters such as layer height, infill percentage, and orientation. Post-processing was performed according to each technology's specific needs, such as support removal and powder removal for SLS. The printed components were then evaluated through both visual inspection and physical measurements to measure and evaluate relevant technical parameters.

Experimental validation focused on key performance indicators relevant to DfAM, such as weight reduction percentage, print time, strength-to-weight ratio, and qualitative comparison of the printed components against their traditionally manufactured counterparts. The outcomes of the analysis formed the basis for further statistical analysis, helping determine the most effective printing technology for reducing design iterations while optimizing performance.

### 3.8 Validation Methodology

The overall validation methodology integrates electronic and physical verification approaches with performance metrics of the workflow to deliver good design validation. Electronic validation involves simulation at multi-scale levels of the component at part, assembly, and system levels, performance metric testing to requirements, virtual testing under nominal and extreme conditions, and statistical analysis of performance variability predicted. This digital process is augmented with rigorous physical verification procedures, including the production of prototypes through industrial additive manufacturing equipment, dimensional accuracy check and comparison to computer models, mechanical test procedures for static and dynamic performance, and functional tests under application-dependent conditions.



**Figure 10.** Integrated validation methodology to validate experimental results *Source: Diagram created using Napkin AI, based on a descriptive prompt (2025).*

To quantify the efficiency of these validation processes, the method defines specific workflow efficiency metrics, including time-to-first-valid-design measures, iterations reduced in number, design quality metrics at equivalent development stages, and resource utilization efficiency comparisons. As a package, these validation components

create an integrated framework for ensuring design integrity while reducing the development process.

This methodology chapter presents an end-to-end approach to reducing design iteration cycles in DfAM processes for performance-critical components. By integrating advanced design tools, implementing stringent validation procedures, and optimizing the entire workflow process from concept to manufacturing, the research work presented in this book provides a framework that is advantageous to both the technical and procedural aspects of AM component development. The subsequent chapters will outline the application of this methodology to various case studies and document the ensuing design efficiency and component performance enhancement.

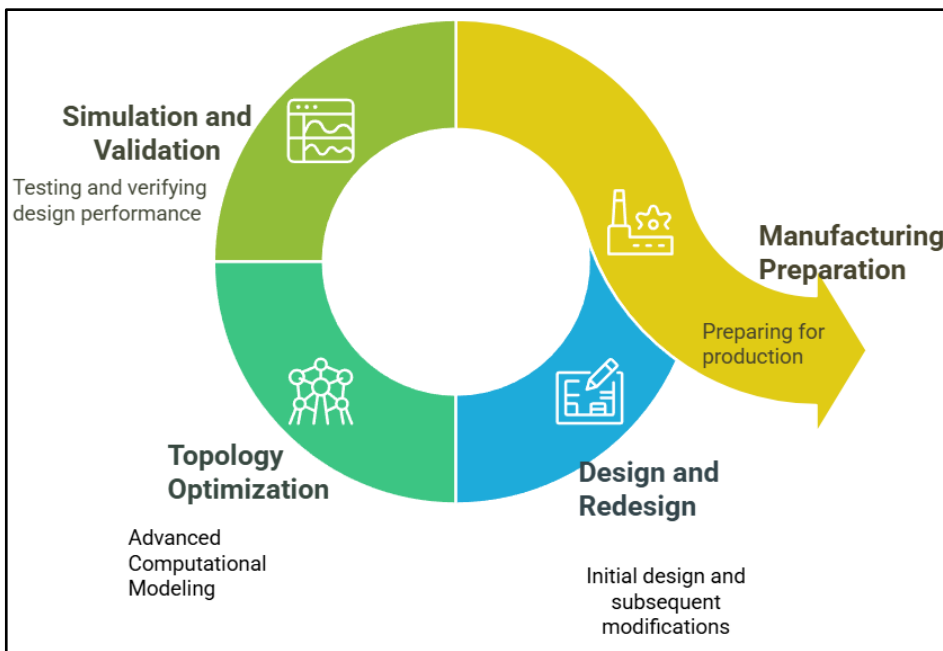
### **3.8.1 Digital Validation**

The validation procedure in the digital process is facilitated significantly by the integration of Altair Inspire's Compensated Geometry feature. The feature enhances the multi-scale simulation validation procedure by adding a manufacturing process simulation that predicts part distortion during the manufacturing process. By simulating aspects such as thermal gradients, residual stresses, and material shrinkage specific to additive manufacturing processes, the software generates compensated geometry that pre-empts expected deformations. Execution of the method involves comparing the simulated printing results and the original design intention, measuring predicted deviations, and automatically generating a modified input geometry that, when subjected to the manufacturing process, will produce a part with close proximity to design tolerances. This predictive compensation approach is a fundamental innovation within the digital validation workflow that effectively bridges the gap between digital design and physical manufacturing while reducing the number of physical prototypes required for validation.



## 4 Design, Optimization, Simulation, and Analysis

The empirical settings of the thesis presented in this chapter, includes design, optimizations, simulations, and analysis carried out related to each use cases will be described. As practicing generative design software approach to optimize the workpath, a general framework is introduced, to reduce design iteration cycles in DfAM. The AM workpath includes software integration identical for each step, design optimization techniques, and process simulation to create a cohesive approach to DfAM for high-performance components, as seen in Figure 11. Additive Manufacturing workpathThe architecture is built around four key pillars: design optimization, lattice integration, simulation validation, and manufacturing preparation.



**Figure 11.** Additive Manufacturing workpath *Source: Diagram created using Napkin AI, based on a descriptive prompt (2025).*

### 4.1 Software Integration

The steps of the AM workflow integrates multiple specialized software tools to maximize the output while maintaining design continuity:

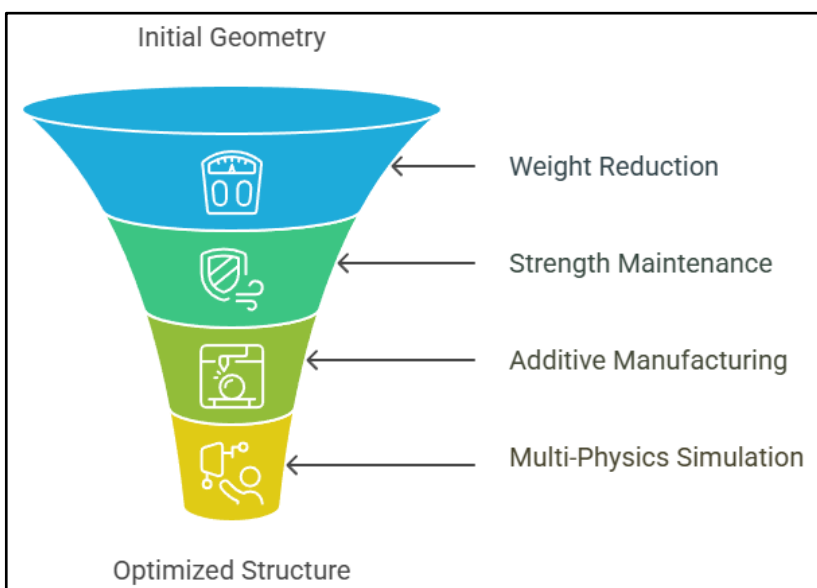
- **Design Creation Layer:** Solidworks and Onshape serve as the initial design creation platforms, establishing base geometry and functional requirements.
- **TO Layer:** Altair Inspire, Altair HyperMesh functions as the primary topology optimization platform, processing design spaces and load cases.
- **Lattice Generation Layer:** Lattice generation is considered as a part of TO, nTopology is specialized in generative design and facilitates in lattice integration intuitively, also its dedicated environment for lattice structure generation and integration offer more controllability and handling features over lattice patterns.
- **Simulation Layer:** Multi-physics analysis measures different parameters stress, strain, displacement and so on. In the simulation phase the component undergoes through different loading conditions, flow patterns and many other different constraints in a virtual environment to understand its durability. This is one kind of non destructive performance validation method in CAE of a component prior to fabricate simulation tools validate designs before physical prototyping.
- **Manufacturing Preparation Layer:** In this phase optimize the configurations to maximize the production, software applications specialized software (Ultimaker Cura, Materialise Magics). 3D printing software to optimize the nesting to increase the number of components to print at a time, avoid overhang constraints, and minimize support structures to reduce post processing.
- **Production Planning Layer:** Production simulation would visualize how best can configure the manufacturing set up using specialized applications ( such Visual Components) to understand the factory layout, orientations of machinery and so on. Additionally, can leverage to forecast the production based on existing infrastructure and due changes can be done based on planning to maximize the production rate. ERP system integration is necessary for factory-level production planning and make the whole process smooth and negotiate bottlenecks.

## 4.2 Design Optimization

Primary designs has been done based on specific requirement (could be 2D or 3D), but prior to its physical prototype, it must be optimized at the design phase. This kind of a skill that optimize the design by designers in different CAD platforms and utilizing generative design software. The modification/ optimoization must preserve the customer specification, on top of that engineers may do changes using different techniques which would generate the best output and sustainable product.

## 4.3 Topology Optimization

The topology optimization is primarily used to reduce the weight , but not to compromise the overall strength, this technique widely used to optimize geometries. Depending on load condition to mimize the mass distribution, eventually would generate light weight structures. The additive manufacturing compliments topology optimization and most of topology optimized components are additively manufactured, where conventional manufacturing methods are impossible to use. Further topology optimization incorporate with multi physics simulation would assist to reduce the number of iterations saving time, resources, and minimizing material wastage.



**Figure 12.** Topology Optimization process to adapt in geometry optimization Source:

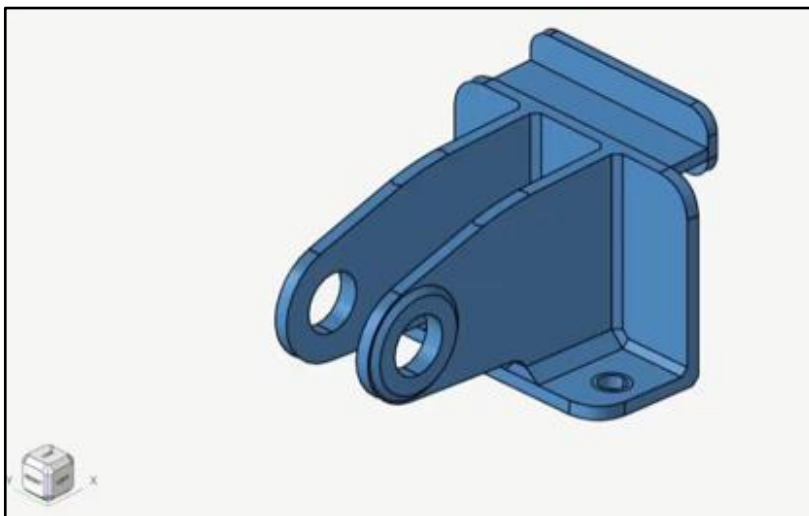
*Diagram created using Napkin AI, based on a descriptive prompt (2025).*

### 4.3.1 Aerofoil Flap Actuator

The framework application to the aerofoil flap actuator demonstrates:

1. Integrated compliant hinges replacing traditional bearings
2. Topology-optimized force transmission elements
3. Consolidated part count through AM design freedom
4. Weight reduction through strategic material removal

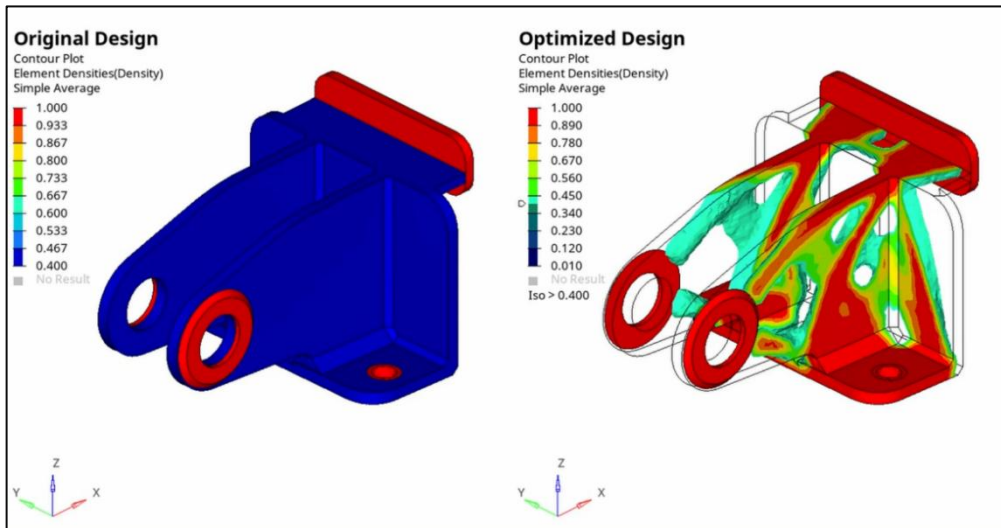
The Flight control flap actuators are critical systems that need to deliver exemplary performance with durability under strict weight and reliability conditions. Optimization of such components has evolved significantly by including advanced computational methods and manufacturing technologies. Modern optimization approaches combine parametric design exploration with topology optimization strategies to come up with high-performance actuator systems that provide optimal strength-to-weight ratios while ensuring functional reliability under severe aerospace conditions.



**Figure 13.** Flap actuator prior to perform TO

The topology optimization has revolutionized actuator design by mathematically determining ideal material distribution, producing organic shapes that efficiently manage load paths with reduced mass. The process identifies and eliminates redundant material while reinforcing primary stress locations, resulting in structurally sound parts with significantly reduced weight penalty.

When paired with additive manufacturing capabilities, such optimized designs are possible with complex internal geometries and part counts reduced to the point of being impossible in conventional manufacturing. The Figure 14 shows a topology optimized flap actuator in Altair HyperMesh, significant weight reduction can be observed, yet maintaining the structural integrity and overall strength.



**Figure 14.** Aerofoil flap actuator – Topology Optimized in Altair HyperMesh 2024

#### 4.4 Lattice Structures

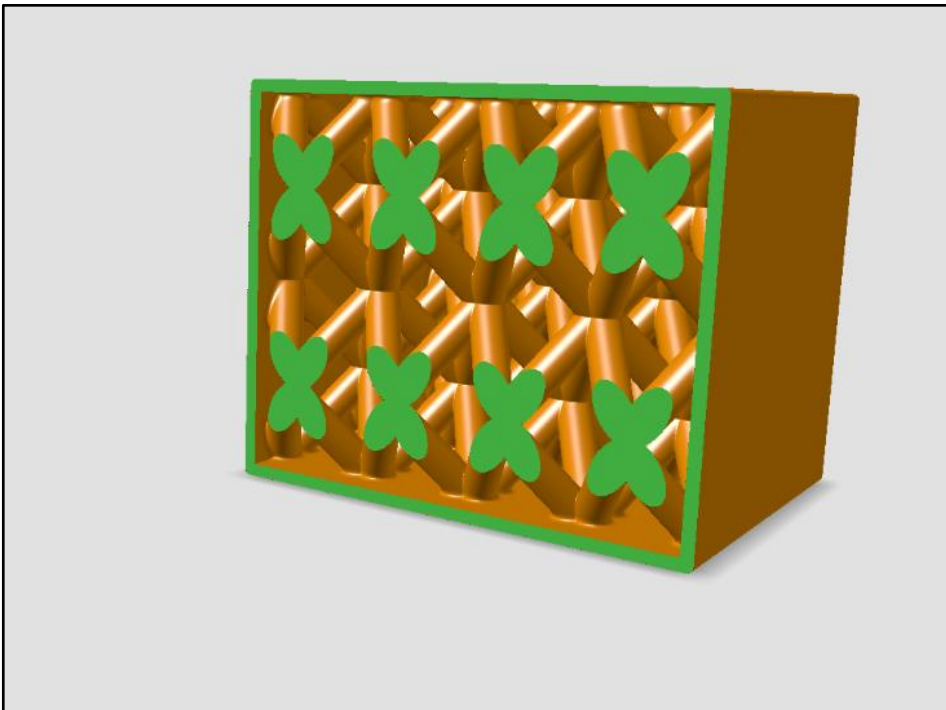
Latticing can be defined as one type of smarter piece of designing, generative design software facilitates widely to develop geometries with advanced techniques. Latticing technologies that enhance the design for additive manufacturing (DfAM) by enabling the creation of complex lattice structures leading to make component lighter in weight, yet more stiffer and durable.

Latticing can be defined as meso-level design elements consisting of repeating unit cell elements in 3D space. Together with additive manufacturing perspectives, lattices would derive many advantages. They reduce an object's mass, which means less material is used. Cellular structures can also give objects extra strength. In the Altair Inspire work bench, Implicit modeling drives lattice creation and geometry modification. Engineers can leverage lattice variations such as Surface, Strut, Planar, and Stochastic based on industry needs.

#### 4.4.1 Lattice Generation Methodology

Modern generative design software takes the lead in latticing technology with unique and advanced features that facilitate engineers to enrich their designs. nTopology latticing workflow has been empowered with third-generation latticing technology. It is enriched with more intuitive and efficient features way to generate lattice structures by splitting the process into three core steps: first one needs to specify the unit cell, then define a cell map according to the orientation of the geometry, and finally can control lattice parameters, and so on.

Once the lattice is applied, then lattice characteristics can be changed according to design parameters. In this case unit cell is Gyroid, and it is optional that the unit cell can be utilized as single/ double and regular/ inverted. Lattice is concerned widely in additive manufacturing perspectives, where lattice must be printable without overhanging and self-supports must be optimized. This optimization can be obtained by changing parameters such density, size of unit cell (along the x, y, and z directions), and changing the orientation of the unit cell to locate unit cells precisely to minimize overhanging.



**Figure 15.** Lattice cell orientation in generative design software platform Altair Inspire

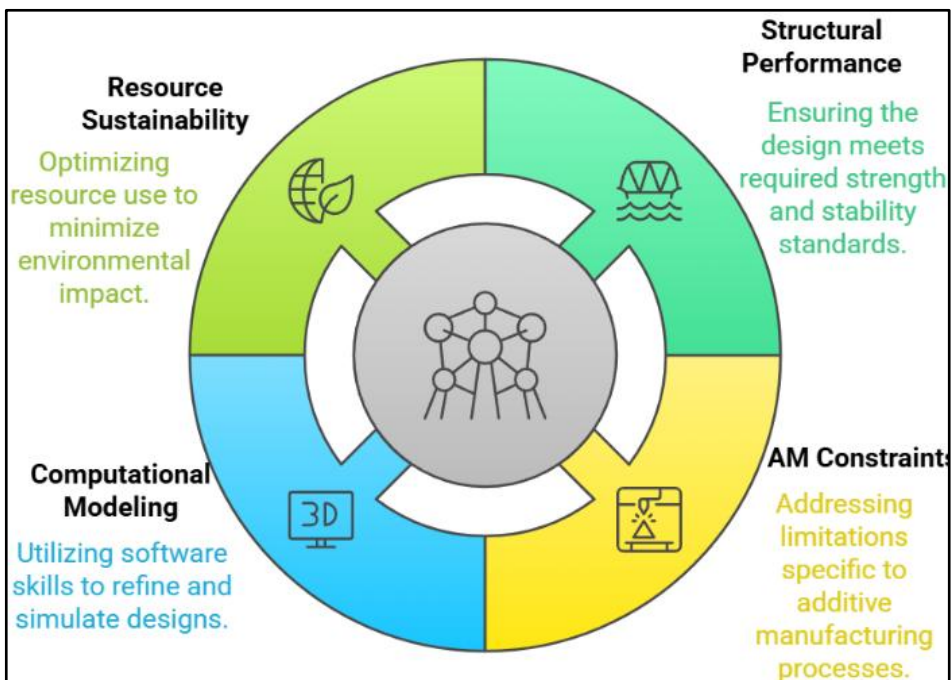
Additionally, in terms of optimizing a part, an assembly, or any other component, engineers' prime responsibility is to think and plan well in advance and use all kinds of design tools to ensure the printability, manufacturability of the product and to reach the desired quality. The Figure 15 illustrates a component that has been optimized in Altair Inspire with lattice integration and changed the orientation (in 40 degrees) to ensure the manufacturability of lattices while preserving the additive manufacturing standards. The section view option in the Inspire workbench can be used to visualize and understand the lattice orientation, and its development along x, y, and z directions when it is printing as the Figure 15 shows.

As the figure illustrates, cross sections can be arranged using the icon that has been highlighted with purple circles inside the purple rectangle down below to understand the lattice development all over the CAD body. Cross sections can be created across all three directions; x, y, z, also moving the respective frame along the way lattice development animates with the CAD body. Additionally, at the top of the model browser there is an option to change the visualization quality from low level to very high. The quality of mesh matters a lot and analyses using slicing software such Ultimaker Cura and Materialise Magics. To enhance the quality of mesh, lattice visualization must be higher depending on geometry that has been used, lattice creation, and topology optimization.

Note: There is no golden rule such, all the time to maintain the visualization at higher; during design iteration engineers must decide the best level of visualization depending on the case.

## 4.5 Multi-Objective Optimization

In the Optimization setup, many parameters must be satisfied while achieving required structural performance. Engineers must ensure that any of the parties should not compromise to make the output more precise. In additive manufacturing point of view, more specialized analysis is necessary to fulfill AM related constraints. The Figure 16 illustrates a map to optimize the additive manufacturing workflow integrating sub processes.



**Figure 16.** Multi-objective optimization in Additive Manufacturing *Source: Diagram created using Napkin AI, based on a descriptive prompt (2025).*

Skills in computational modeling are essential to optimize the design for additive manufacturing starting from the handling the CAD modeling software to advanced computational modeling software and 3D printing software along the way, there are many constraints to consider and to be proactive with geometry handling techniques, optimize the design, and maximize the manufacturing capacity ensuring sustainable use of resources.



## 4.6 Components Design and Development

The components have been divided into few categories based on inherent characteristics, and described as follows.

### 4.6.1 Structural Components

The development methodology for structural components ( satellite assembly, hydrofoils, drone wing, and biomimetic spring mechanism) follows a systematic approach:

1. Initial requirements analysis (may be received from a customer or stakeholder) and loading conditions.
2. Preliminary design space definition based on installation constraints, define the software requirement for basic CAD modeling and assembling.
3. Advanced computational modeling. Import the CAD model to generative software available for Multi-objective optimization.
4. Perform FEA validation and refine the structure based on results and requirements have been specified. Topology Optimization or Generative Design can be used for advanced optimization.
5. Leverage capabilities of generative design software for lattice Integration for subjected structures using for weight reduction while maintaining performances such overall strength, structural integrity and so on.
6. Employ 3D printing slicing software for further design refinements to meet manufacturability constraints specific to the selected AM technology.

### 4.6.2 Functional Components

For functional components (aerofoil flap actuator, automotive parts like connecting rod, camshaft) the approach is bit more advance since those are subjected for various

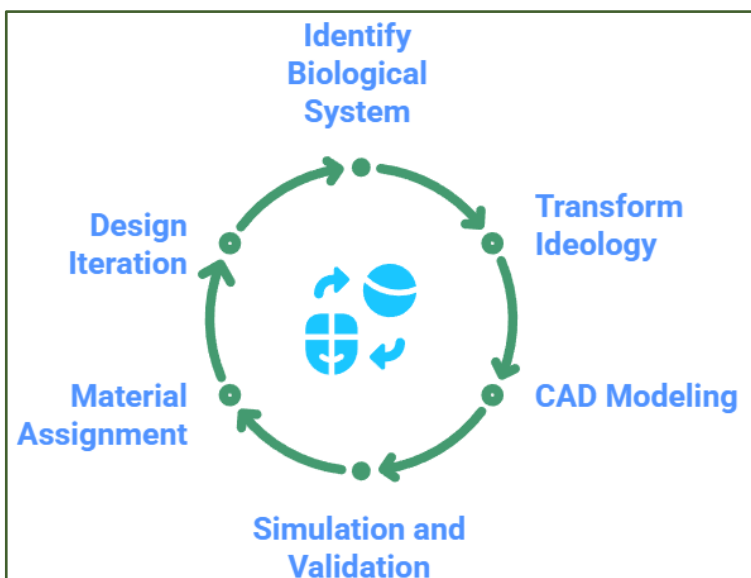
different loads and stresses. Therefore during the design space all kinds of constraints must be considered and the methodology includes:

1. Functional requirement specification (loads, stress, possible displacement limits, specific tolerance limits, material specifications, and other subjected components) and performance metrics definition.
2. Kinematic analysis and motion envelope determination to ensure that design phase covers all necessary constraints for the proposed component.
3. Once basic CAD modeling has been completed successfully according to the dimension and other geometry specifications, can implement the Topology optimization with functional constraints
4. Generally, materials are specified by customers or stakeholders, and also Material selection can be done based on both mechanical and thermal requirements.
5. In the process of additive manufacturing, process-specific design adaptations is necessary for further refinements upon due selecting the process to fabricate. (special consideration on surface quality, avoid overhang, minimize support structures, build orientation optimization, nesting optimization to increase the rate of production and time saving)
6. In the design phase post-processing requirement must be integrated, while performing advanced computational modeling in generative design platforms.

#### **4.6.3 Biomimetic Compliant Mechanisms**

Biomimetic compliant mechanisms have distinguish characteristics, and their applicability requires special concerns. Hence the development phase of biomimetic compliant mechanisms must follows a distinct methodology to preserve its inherent characteristics.

1. First need to identify a specific biological system, component or any other mechanism to analysis and abstract the functional performances.
2. Ideology transforming to apply for a suitable engineering application is critical, by realizing the specific biological principles to apply mechanical design parameters.
3. Required basic CAD modeling has to be done in Solidworks and Onshape, such as Compliant joints, bodies, connectors and flexure development.
4. Originally biological structures are subjected to non-linear movements and deformation, since due simulation must be implemented follow up with results.
5. Biological systems has own damping systems to allows for elastic movements, where biomimetic compliant mechanisms also should be able to mimic same movements with optimal elastic response. Since assigning material is crucial to obtain the desired flexibility.
6. As biomimetic compliant mechanisms should fulfill additional requirement to achieve desired shape, movements and other characteristics, design iteration must be implemented with seamless integration of all sub process of AM.



**Figure 17.** Biomimetic mechanism development cycle *Source: Diagram created using Napkin AI, based on a descriptive prompt (2025).*

Since biomimetic mechanisms are enriched with nature inspiration design iteration loop has added value features to exercise during the design iteration to generate fully optimized output. Value added insights illustrates in the Figure 17.

#### 4.7 Case Studies

In this research, case studies have been selected from the aerospace and marine industries, components are a hydrofoil, an aerofoil, and a satellite structure. These types of parts were selected based on their suitability for advanced computational modeling using generative design software. Each case study is a complete process that involves initial design or redesign through advanced CAD software, followed by simulation and analysis for performance improvement evaluation.

The hydrofoil and aerofoil geometries have been developed from scratch and employed for topology optimization, lattice structure, flow simulation, and other suitable analyses for additive-focused enhancements. For the satellite component, however, they began with a pre-existing CAD model that was then further optimized using simulation-driven optimizations. The shows the list of candidate components employed in the thesis including correspond operations have been performed.

**Table 7.** Components employed for case studies

S/N	Component	Design Approach	Computational Modeling	Optimization Method	Printing Technology
1	Cubesat Structure (U1)	Conventional	Basic CAD	Manual	SLS
		DfAM	Altair	Lattice Integration	
2	Cubesat Structure (U2)	DfAM	Basic CAD	TO + Full lattice integration	N/A
			Altair + nTopology		
3	Hydrofoil	Conventional	CFD (Basic)	Manual	FDM
		DfAM	Altair	Hydrodynamic Opt.	
4	Aerofoil	Conventional	Basic CAD	Manual	FDM
		DfAM	Solidworks, Altair	Aerodynamic Opt.	
5	Biomimetic Spring	Conventional	Basic CAD	Manual	SLS
		DfAM	Altair + ANSYS	Bio-inspired Opt.	

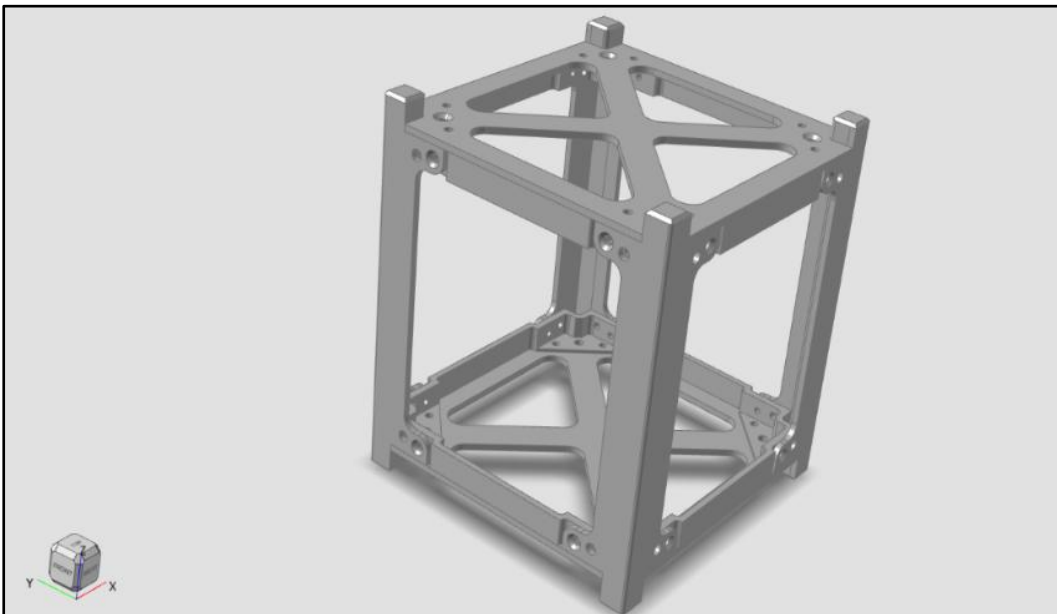
Each component is subjected to mechanical simulations using Finite Element Analysis (FEA), and, where necessary, thermal and aerodynamic performance were analyzed through Computational Fluid Dynamics (CFD). This systematic case study approach not only established the effectiveness of DfAM but also highlighted the unique strengths and limitations of various additive manufacturing processes (e.g., SLS, FDM).

#### 4.7.1 Satellite structural component optimization

Cubesat is a special category of nano, dimension of a cubesat is 10 x 10 x 11 centimeter, then the requirement is to design a lighter and stiffer structure. In the phase of optimizing the structure as shown in the Figure 18, from additive manufacturing point of view several requirements can be fulfilled as follows:

1. Assembly consolidation to minimize the vibration
2. Generate much stiffer structure to withstand loads
3. Optimize the material usage depending on the loading conditions
4. Mass reduction strategies while maintaining stiffness requirements

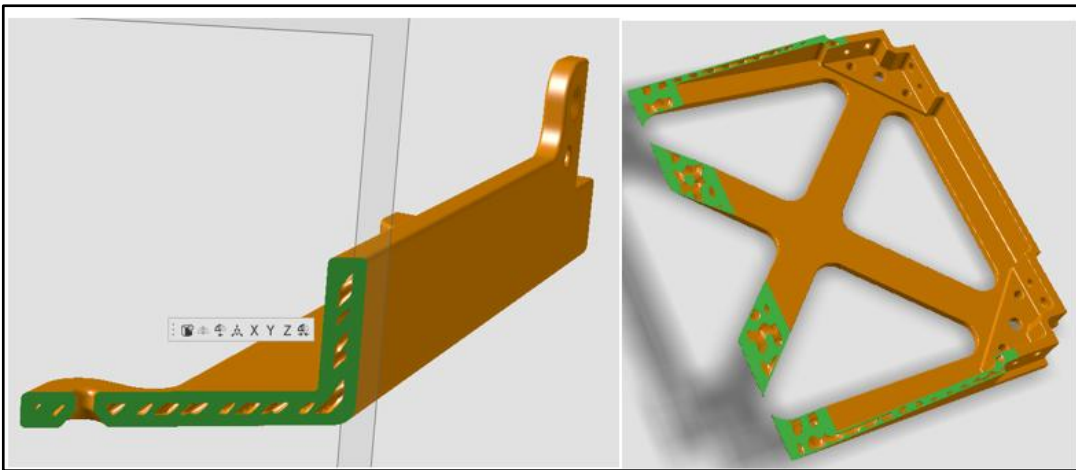
Each part of the structure has been separately optimized by embedding lattice as follows.



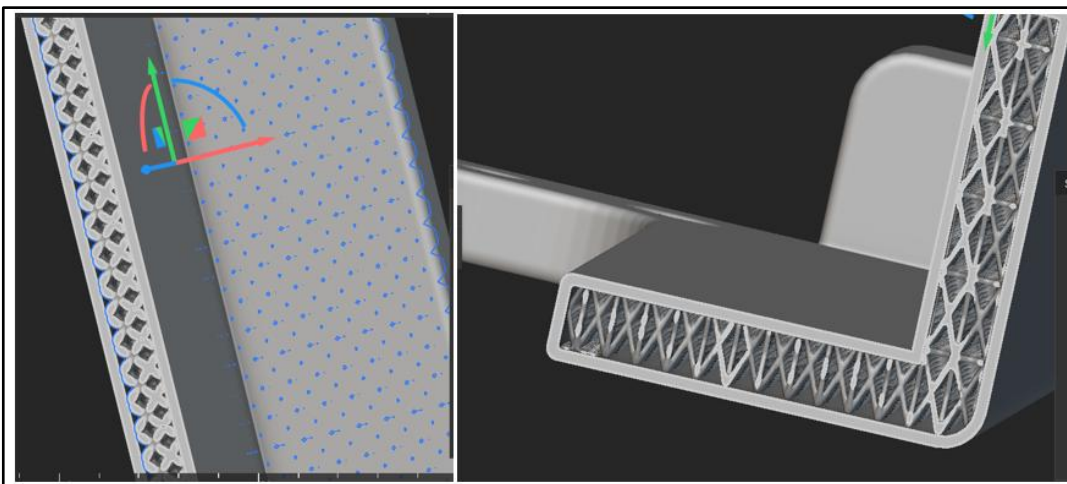
**Figure 18.** Cubesat Bus Assembly structure, a pre modelled CAD body

For the basic CAD modelling and geometry splitting were completed in Onshape, and two generative design software (Altair and nTopology) have been utilized for advanced computational modeling, lattice integration and geometry optimization.

In lattice embedding, many software can be leveraged with their distinct features, handling the lattice cell is crucial to avoid overhang and minimize support structure. Also, the quality of mesh play a vital role in physical prototype to print a much precise component which satisfy necessary constraints. The Figure 19 and Figure 20 show the lattice embedding in two competitive generative design software, which are versatile in many areas of computational modeling paradigm.



**Figure 19.** Lattice integration for the satellite structure in Altair Inspire (2024)

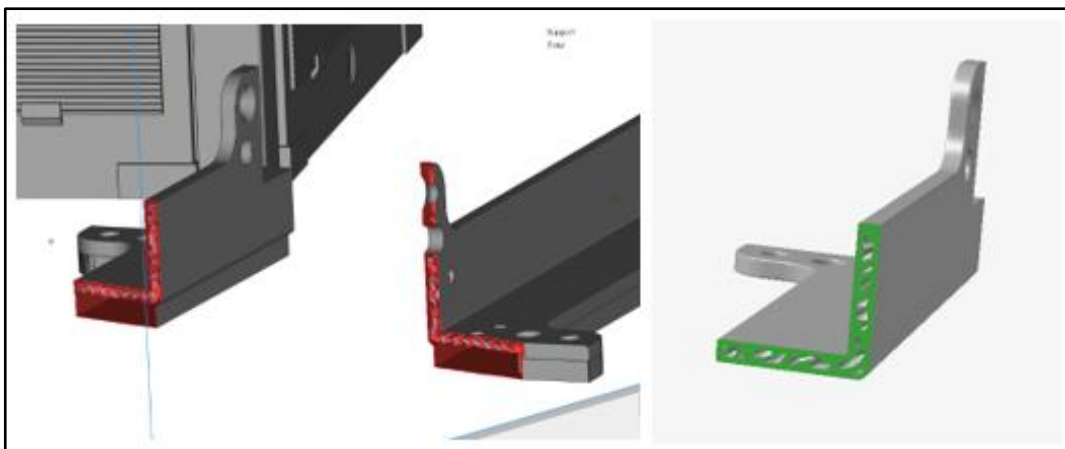


**Figure 20.** Lattice integration for the satellite structure in nTopology

As figures illustrate each software has their own process in lattice embedding, while Altair provides series of platform for each category on computational modeling, and nTopology has a unique workbench for all operations.

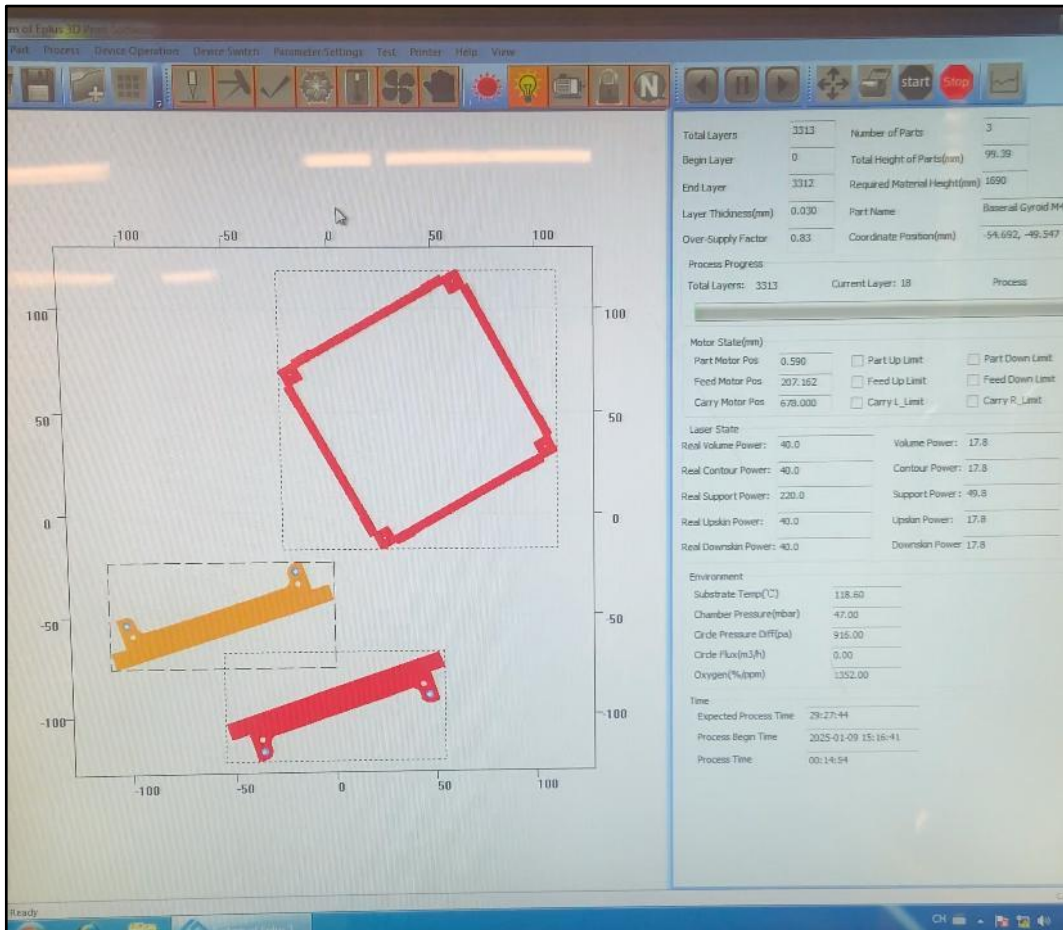
Once the modifications, top of that topology optimization and lattice integration has been completed, the component would export as a STL file for the slicing depending on material specification. Generally, for plastic prints Ultimaker Cura is the most common one, but this satellite component was planned to print in metal, Aluminum was chosen due to its inherent material properties suits for light weight structures. The slicing for metal Materialise Magics was utilized, is well versed in slicing for metal printing. Further refinements such as visualization quality, check and clean the mesh, removing support structures, nesting and final preparation as shown in Figure 21 the perform to make the print output closely align with the desired specifications.

At this point, parameters of the component such as lattice orientation, lattice density, inward-outward cell thickness, mesh and export quality etc are assessed. If the engineer isn't satisfy with certain parameters of the component, can exercise the design iteration loop, and rectify the wherever necessary. This software integration framework assist to follow the steps in the iteration and modify design until it reach to desired standard, on flip of the side framework supports to reduce physical prototypes redundancy in a sustainable approach.



**Figure 21.** Computational Modeling Operations in Materialise Magics

After performing several iterations, can finalize the design with accepted quality standard, due completion of advanced computational modeling and components are ready. Then real metal printing commences in the printing machine, and as shown in the Figure 22 computer screen of the printing machine will display components are printing and other machine parameters are there to control during the print.



**Figure 22.** Arranging build orientation and nesting in printing machine control panel

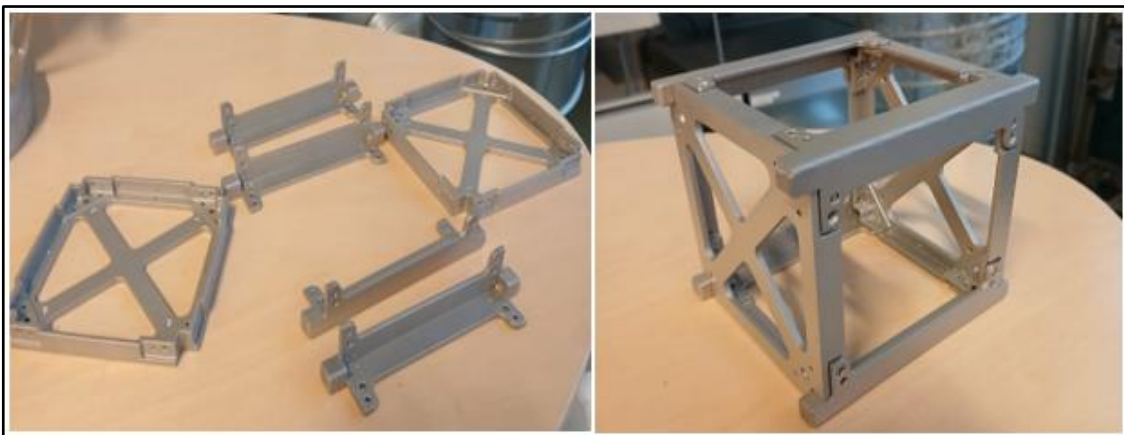
A layer by layer, the machine print components as shown in the Figure 23. Laboratory Engineer may deal with the machine parameters as the print is going on such as temperature, pressure, gas and powder level must be monitored consistently to ensure all the parameters are within the accepted range.





**Figure 23.** Metal printing of Cubesat satellite components in Prima Additive

Generally, parts will be printed on a metal palte called as base plate, Upon completion of printing, parts detach from the base plate and must do the post processing to clean and obtain the surface finish to make the component visually appealing as shown in the Figure 24.



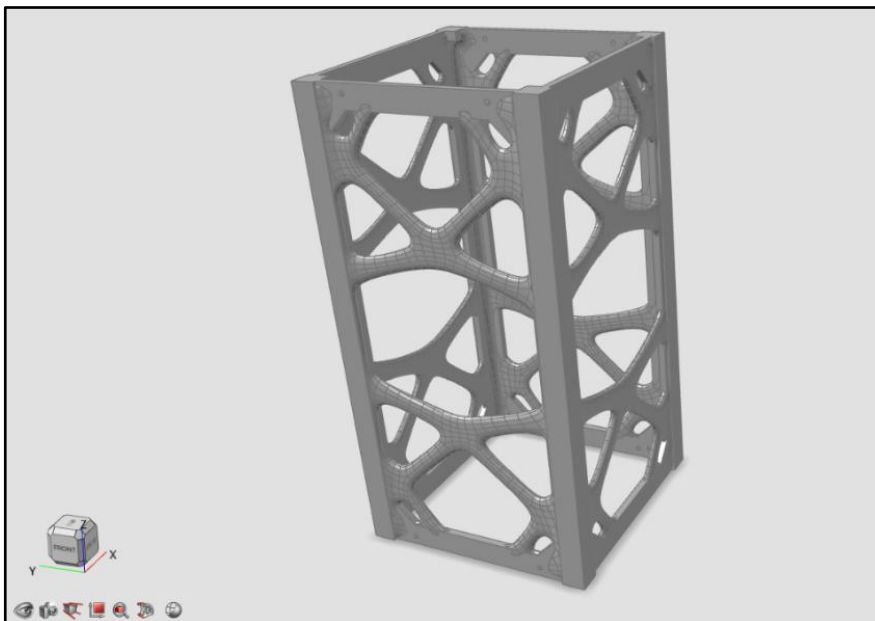
**Figure 24.** Printed satellite parts of the Cubesat satellite

#### 4.7.2 Structural optimization with full lattice integration

The full lattice integration gives extra refinements for a components, specially in structural optimization lattice integration assist in optimizing mass distribution while maximizing the structural integrity.

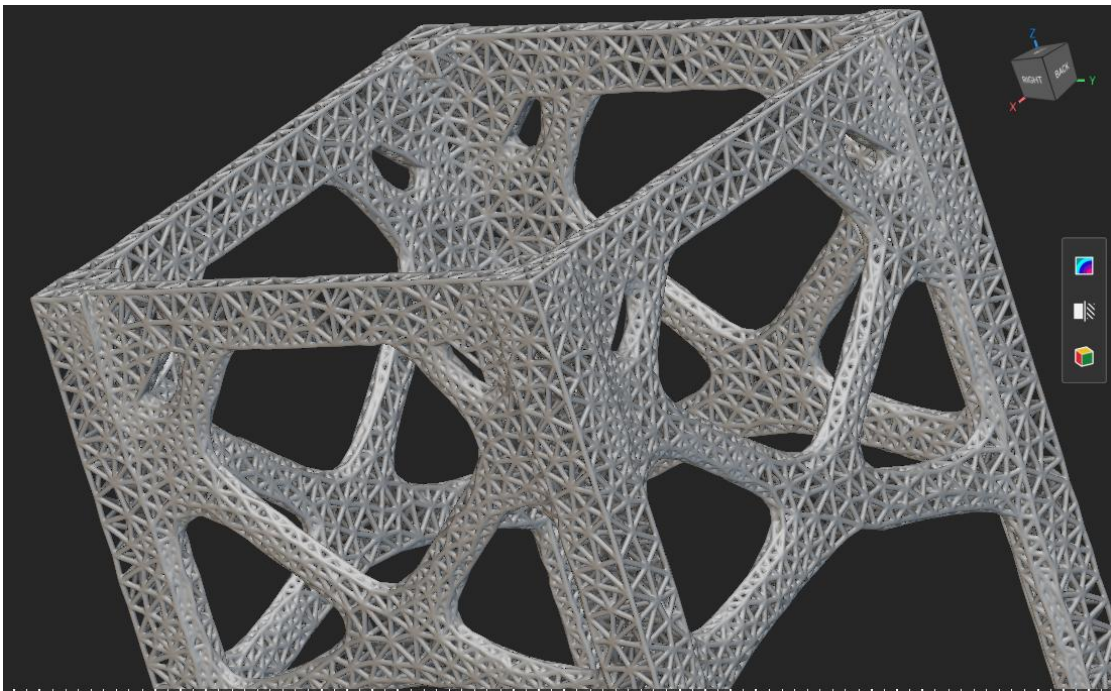
In terms of lightweighting lattice integration is a wise decision with by using precise tools. The following shows a structural components which is after design optimization. Due considering the requirement of embedding lattice few factors to be considered, specifically design space, type of lattice cell type, orientation of the lattice cell, support structures and so on. There are various lattice cells can be found in catalogues in generative design software, out of them, Gyroid is the most popular lattice cell type, other than FCC and BCC are often, additionally there are many to choose depending on the requirement.

The lattice integration starts with a STEP file of a CAD model designed in a CAD software, then it must be imported into a generative design software platform for advance computational modeling . The Figure 25 shows an extended CAD model of the Cubesat satellite structure, this is two times bigger than the generic Cubesat bus assembly, and known as U2.



**Figure 25.** Optimized U2 satellite structural component

Upon completion of basic CAD modeling, the TO has been performed in Altair to generate more feasible structure while optimizing the mass distribution to maintain structural integrity. Then for further optimization with full lattice integration nTopology has been chosen since its unique and advanced features that facilitate engineers to enrich their designs. nTopology latticing workflow has been empowered with third-generation latticing technology. It is enriched with more intuitive and efficient features way to generate lattice structures by splitting the process into three core steps: first one needs to specify the unit cell, then define a cell map according to the orientation of the geometry, and finally can control lattice parameters, and so on. This modeling approach simplifies the complexity of latticing workflow for engineers to modify designs seamlessly. The Figure 26 shows fully lattice embedded structural component in the nTopology work bench.



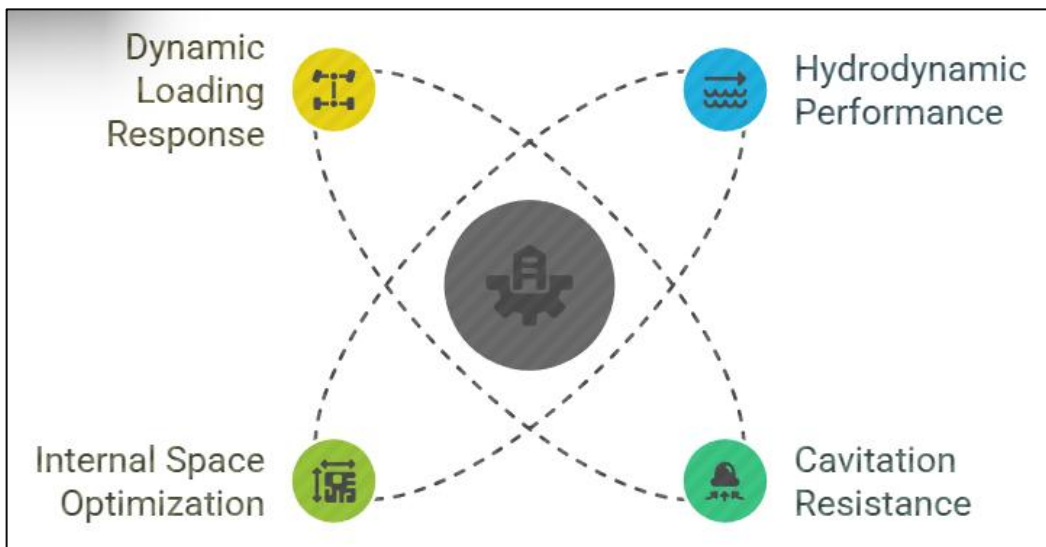
**Figure 26.** U2 Satellite structure full lattice integration by tetra lattice structure

The full lattice integration offers various benefits for structures such as best option for light weighting, porosity free, structural flexibility and so on. Additionally, nTopology facilitates with intuitive features in creating full body lattice can be seen in the Figure 26. U2 Satellite structure full lattice integration as ntop notebook has been developed

to generate desired geometry. The pathway is clear and platform itself supports for designers to choose the consecutive steps and real time troubleshoots.

### 4.7.3 Hydrofoil Optimization

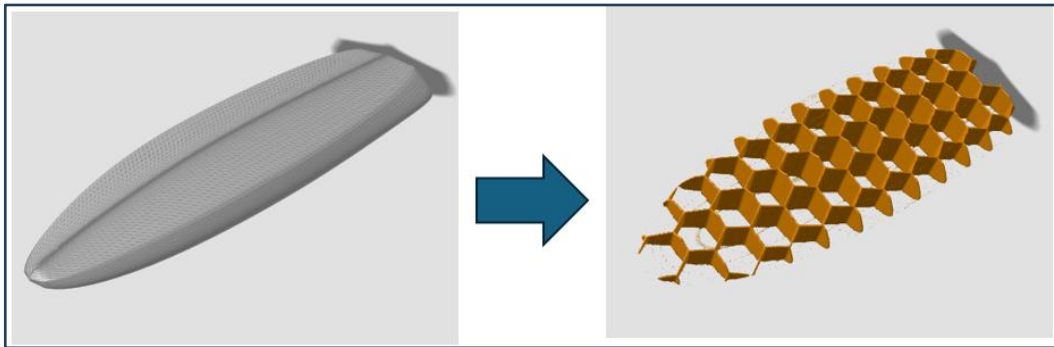
Hydrofoils are one type of widely used component which require robustness to withstand loads and geometry optimization to negotiate various flow patterns in a marine environment.



**Figure 27.** Factors to enhance structural durability of the hydrofoil Source:Diagram created using Napkin AI (2025).

Hydrodynamic performance is the most crucial parameter of a hydrofoil, and during the design phase engineers must ensure the design satisfy hydrodynamic aspects, since it directly impacts the efficiency and speed of watercraft. Additive manufacturing, simulation phase to test the hydrodynamic performance and to optimize the geometry until reach to the required standard. This is kind of an iterative development process, generative design software platforms can be used prior to physical prototypes to validate the design which leads to reduce the design iterations. AM facilitates to optimize the material utilization which would benefit for hydrofoils and aerofoils kind of components to prevent damages to its geometry. Also, additive manufacturing allows for advanced and precise material distribution to enhance cavitation resistance.

Further, to acquire extensive stability and ensure the functionality, internal space optimization is crucial; due consideration Additive manufacturing techniques facilitates the creation of complex internal structures that can enhance stability and stiffness without increasing weight. Moreover, hydrofoils must perform well under various operating conditions, including different speeds, loads, wave patterns, and environmental conditions. Additive manufacturing allows for the creation of designs that can dynamically respond to these conditions through design iterations, where CFD simulation can be used for the performance evaluation under various environmental conditions, and FEA can be used for multi physics analysis to generate more durable design.



**Figure 28.** Software integration during the design phase of Hydrofoil

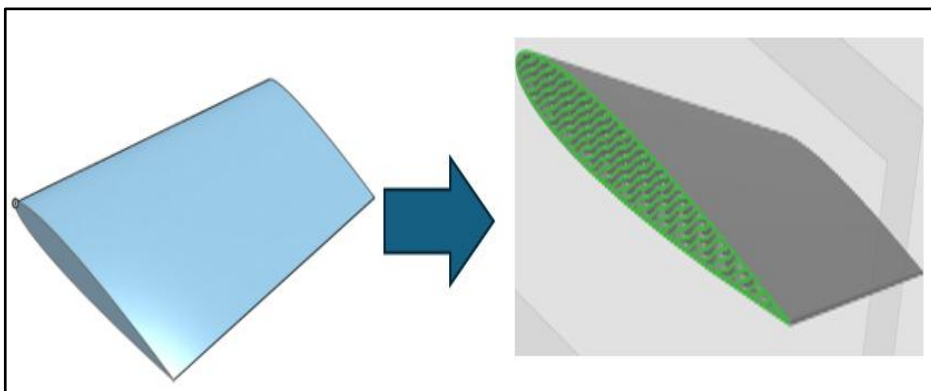
The left side of the above figure shows a primarily designed hydrofoil in a CAD software prior to optimize. At the basic design, must get the desired shape of an object. Then it would import to a generative design software as shows in the right side. Generative design software for advanced computational modeling such as weight reduction, lattice integration, and CFD simulation etc.

For this hydrofoil; vertically oriented Planar lattice has been integrated considering the direction loading conditions. Next step is to go for the prototype simulation to give it a real environmental conditions and test it in a virtual environment to test for its durability to visualize the performance. Based on derived simulation results, further geometry optimization can be done in the CAD, then in the generative software platform and so on. This iteration could be minimized depending on the software utilized and skill level of the designer.

#### 4.7.4 Drone Wing structural optimization

Aerofoils are also, similarly or even more crucial components compared to hydrofoils; necessarily to be optimized to reach performance level due to its critical operating conditions need to encounter. Additive manufacturing (AM) is one of specific technology which offers much possibilities to modify, develop, and optimize based on its geometry and utilization. It is a significant advantage in optimizing drone wing components by addressing aerodynamic performance.

Additionally, AM facilitates in generating stiffer and light weight profile to withstand asymmetric loading conditions while preserving its performance to maintain flight dynamics. CFD simulation could specifically be used for aerofoils to analyze under different loading conditions, winds and various turbulence patterns to ensure that the wings can handle uneven loads. This would assist engineers to ensure wing structure is more durable and reinforced prior to physical prototype validations. All in all, material distribution balancing for flight dynamics is critical for maintaining stability and maneuverability. Additive manufacturing facilitates in material usage optimization, without compromising the overall strength, yet ensure the optimal weight distribution across the component. Leveraging various techniques AM could enhance the overall performance of drone components.

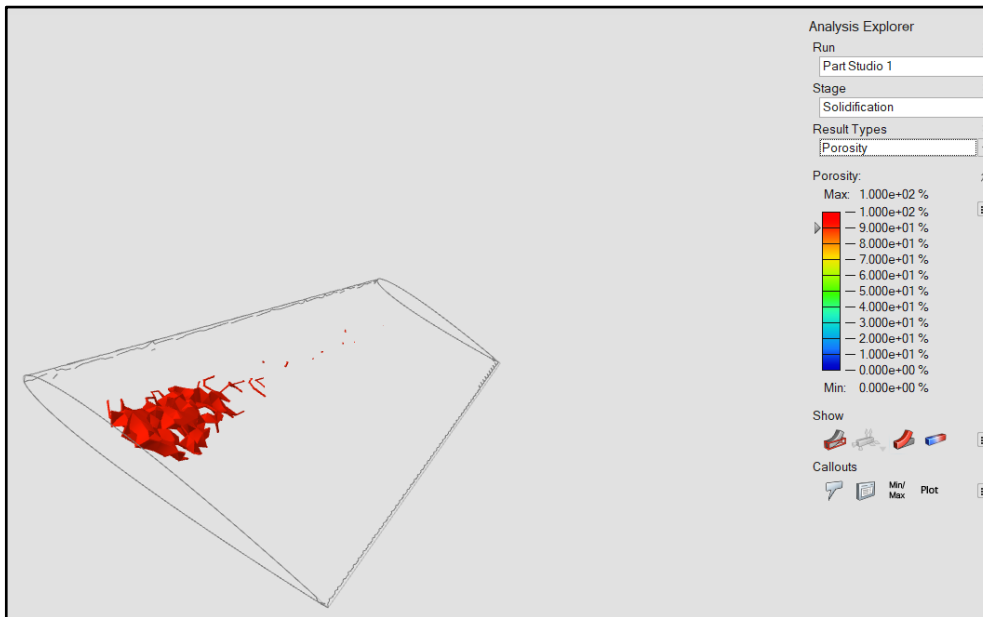


**Figure 29.** Software integration for design optimization of Aerofoil

Focusing on further optimizing the design and minimizing the redundant prototypes, porosity can be analyzed using generative design software prior to fabrication. This porosity analyzing capability addresses head-on one of the primary problems in the



optimization of additive manufacturing processes - physical iteration minimization required to create specification-compliant parts. With the addition of this digital validation process after design completion but before production commitment, the number of physical prototypes required was reduced by approximately 60%, with the same reduction in development time.



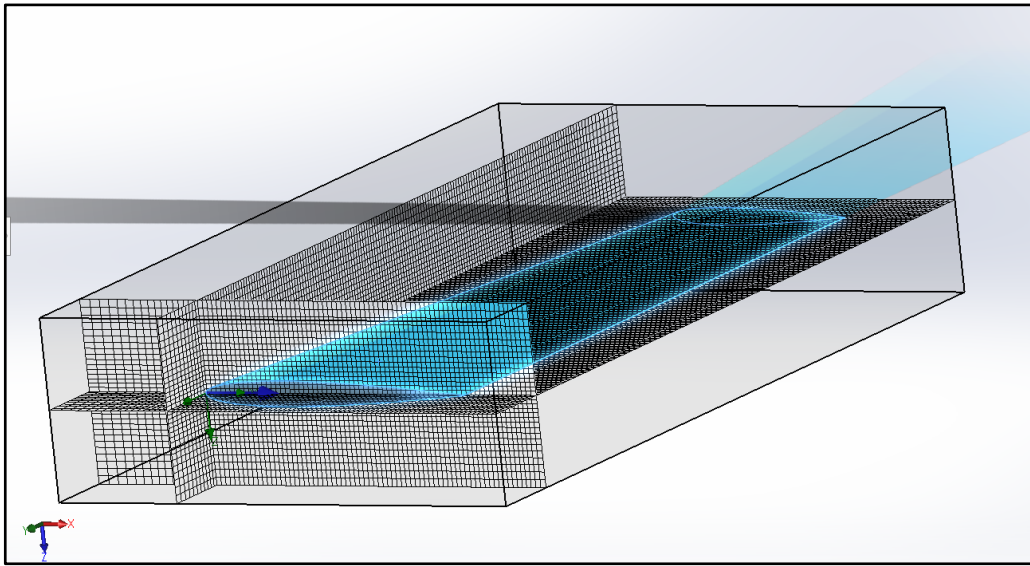
**Figure 30.** Porosity analysis of the aerofoil in Altair Inspire (2024)

These analysis offered better decision-making regarding part orientation and support structure location to minimize porosity in structurally significant regions, thereby providing a stronger connection between design intent and manufacturing execution. Furthermore, generative design software supports for the analysis of various physical parameters such as porosity, microporosity, temperature distribution, shrinkage, and geometric modulus etc. On top of that, implementing a case sensitive analysis in a virtual environment would be beneficial to understand the behavior of the component in the actual environment.

Additionally, this feature enhances the scope of the framework suggested in my thesis, where to minimize the design iterations and physical prototypes followed up with real-time simulations. The case sensitive analysis is set upon based on the ground conditions of the particular component supposed to be operated. For an example; an aerofoil operates in

air, a hydrofoil operates in a marine environment, likewise ground conditions vary according to the applications and purpose.

The Figure 31. Applying BC for the aerofoil flow simulation in Solidworks shows that applying boundary conditions to run a flow simulation for an aerofoil. Theoretically, by this point 75% modifications must be completed, and upon running the simulations under various ground conditions engineers may optimize the design for better advancements.

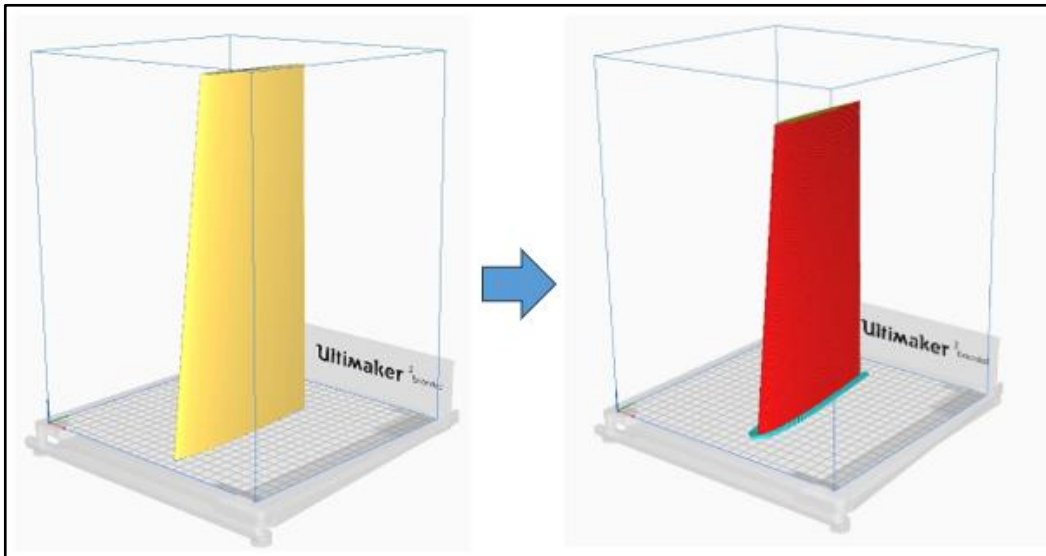


**Figure 31.** Applying BC for the aerofoil flow simulation in Solidworks (2023)

Due applying BCs, can observe how flow patterns move around the profile, and based on that engineers may refine the basic design and optimization further to obtain a finest version. This approach would assist in visualize real ground scenarios in a virtual environment, can perform without having a physical prototypes, additionally mitigate the risk of failing final products.

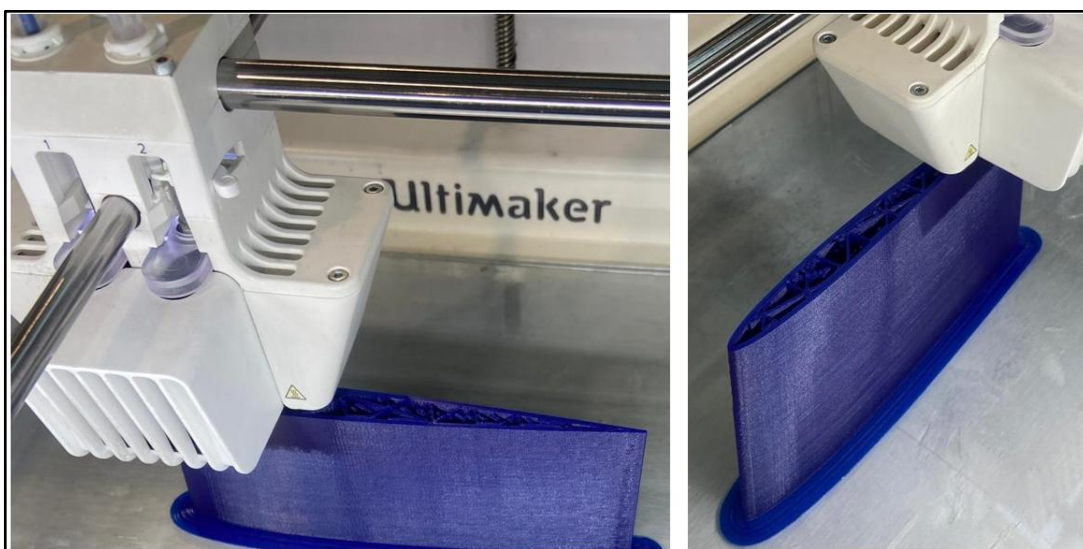
Once the engineer or designer satisfies with the performance of the component such as design constraints, FEA, flow simulation and analysis, ready for to fabricate the first physical prototype using specified material. The Figure 32 shows how does the aerofoil is prepared for the printing, first need to import to the slicing software tool either Materialize magics (for metal printing) or Ultimaker Cura (for plastic printing).





**Figure 32.** Importing and slicing the aerofoil in the Ultimaker Cura

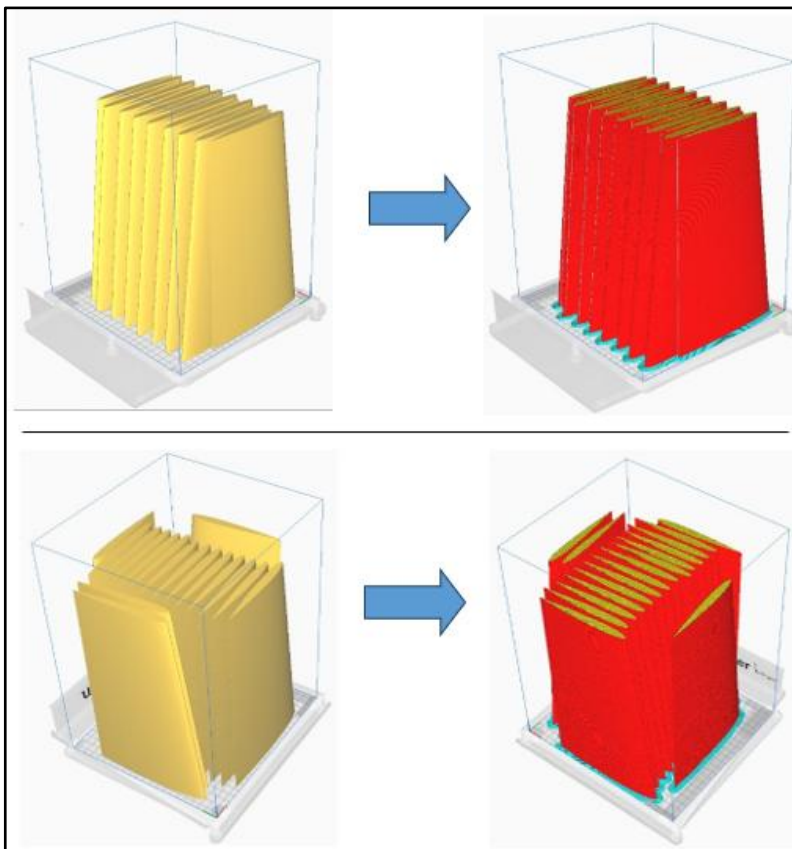
In the software settings of the Ultimaker can define the distinguish parameters for a component identically, Infill percentage assist in maximize the material distribution and reduce the print time, build orientation to position the component on build platform focusing to minimize the overhang and support strucre, impacting its quality, strenght,and print time. Additionally, the print speed to print the component with desired surface quality. The figure shows how has it been printing in the Ultimaker printing machine according to given specifications.



**Figure 33.** Printing the aerofoil in Ultimaker (infill pattern and outlayers are shown)

Moreover, in the context of a factory setting run on a business plan curious to maximize the production output while saving time, electricity, and other infrastructure. The Nest orientation of components facilitates to increase the production by strategically arranging and positioning multiple 3D model within a single build platform. The nesting configuration can be decided by the designer based on either requirement or business plan, expected rate of production.

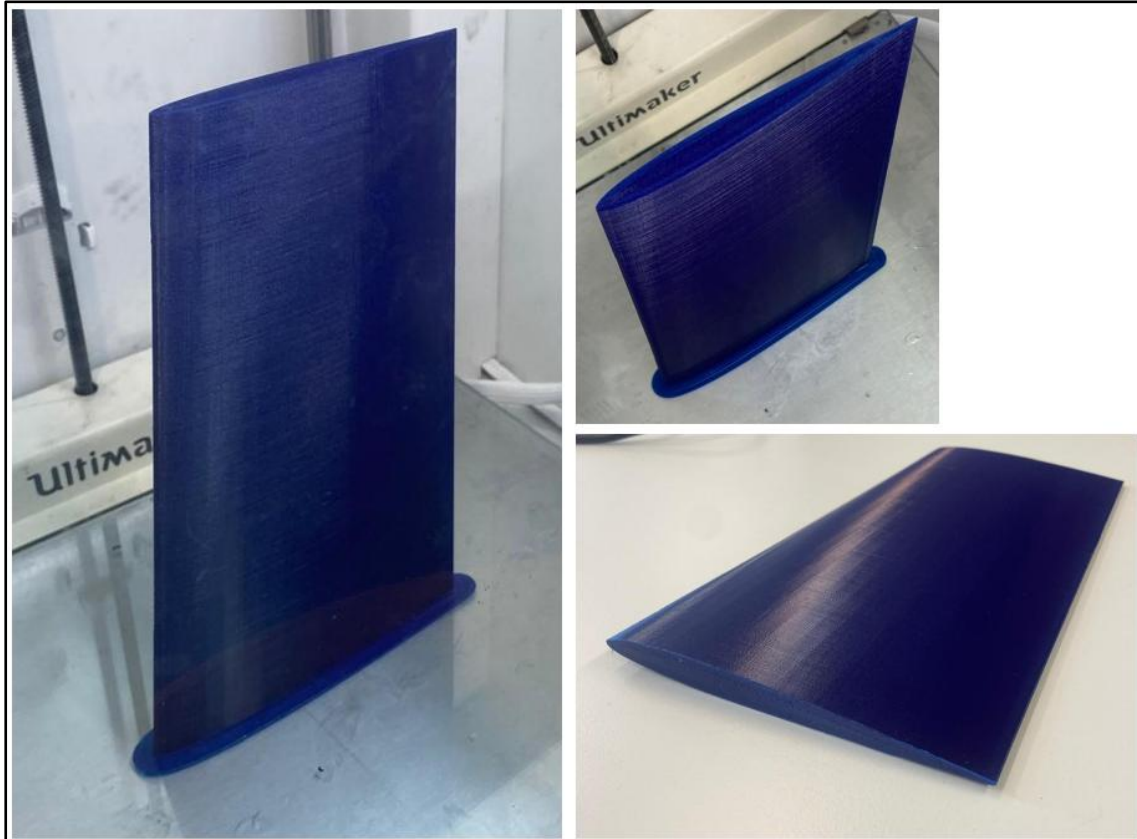
Additionally, the Ultimaker Cura assist in automating nesting upon specifying the number of component needs to print at a time, hence designers may choose the best nesting configuration to satisfy the given constraints. The Figure 34 shows the two different nestings with multiplied aerofoil 3D models imported and correspond slicing to maximize the aerofoil production.



**Figure 34.** Different Nesting configurations obtained in the Ultimaker Cura platform

Upon developing this thesis, an aerofoil only printed lasted for seven hours in the past resolution, with 0.2mm nozzle have been employed to print the component. With the nozzle of 0.2mm utilized can generate very detailed print quality to manage the

tolerance. The fabricated material is Polylactic Acid PLA as the default filament of choice for most extrusion based 3D printers, with 20% of infill density and triangles pattern with 0.8mm shell thickness. Upon successful completion of printing full prototype of the aerofoil is shown in the Figure 35.



**Figure 35.** Printed full prototypes of the aerofoil

The digital-physical validation bridge is emblematic of the integrated methodology to manufacturing workflow optimization that is at the heart of the method presented in this research. Objective is to define the seamless integration of software platforms to achieve desired efficiency by reducing design iterations and physical prototypes to develop sustainable products across industries.

## 4.8 Biomimetic Design Implementation

Nature-inspired biomimetic designs have become increasingly prevalent in industrial applications due to their inherent durability and easy adoption to different operating conditions, creating a revolutionary movement in modern engineering. Deployment of biomimetic design is a formal process through a functional abstraction methodology that, in a systemic manner. Deconstructs biological systems, maps their function into engineering needs, quantifies the dimensional and performance metrics of interest, and applies scaling techniques that preserve functional principles while spanning the needs of industries.

The Following compliant mechanism shown in the Figure 36 has been designed to mimic the movement of a bird's feather, where each rod suppose to turn 30 degrees relative to the previous one. Due to the design configuration has embedded the spring nature, each



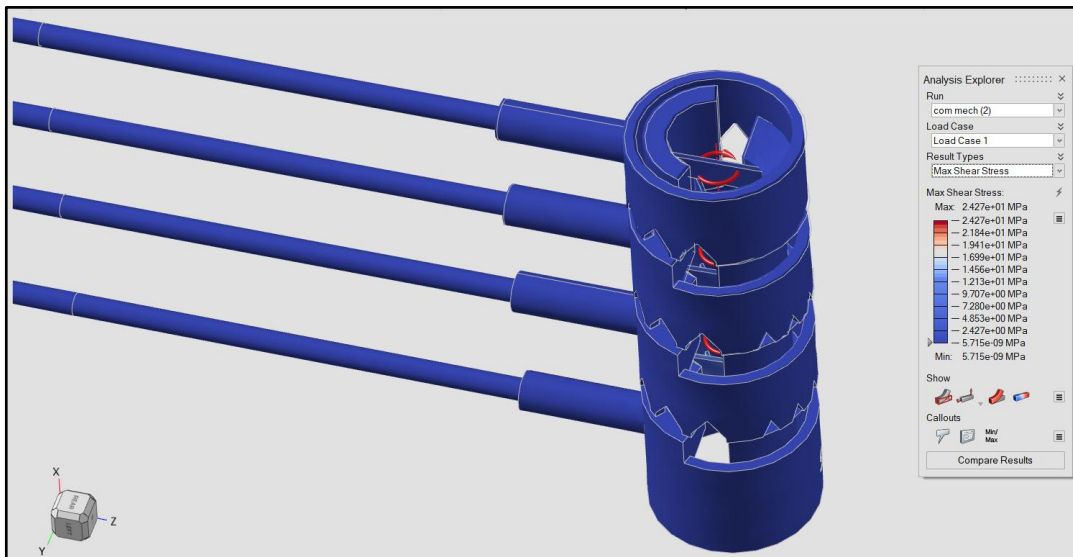
**Figure 36.** Biomimecking spring mechanism CAD model in Onshape

circular part can rotate individually, this motion could potentially be applied to any kind of suitable mechanism to function with extra flexibility.

Further emphasizing, biomimecking has become more advance as integrating new features and trying to give more nature biased facet and configurations. Strat from the

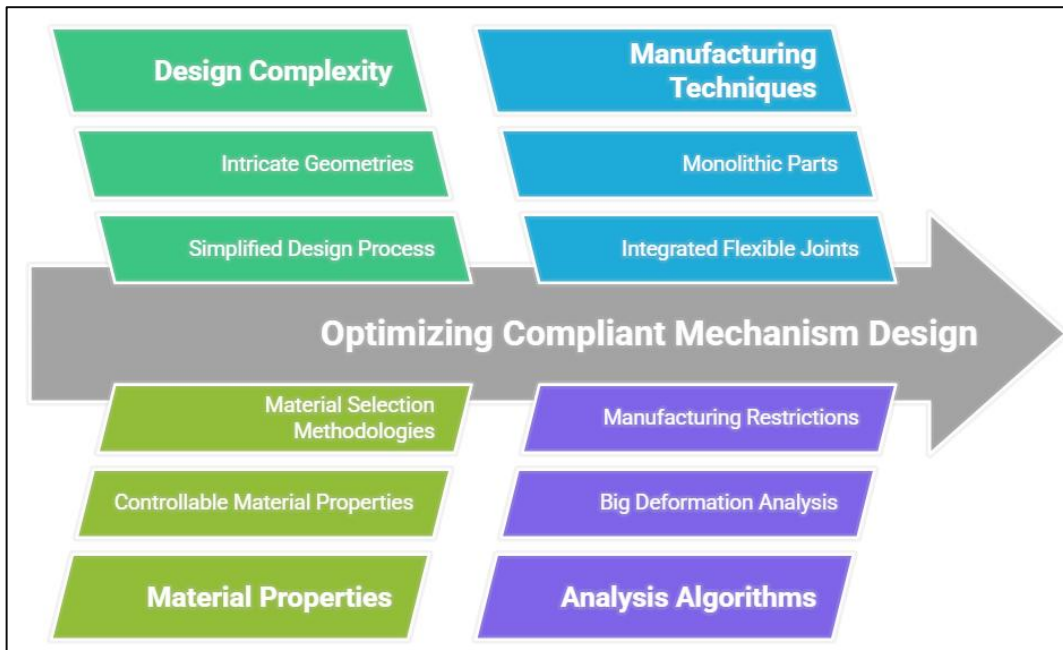
scratch, develop it as a workflow to develop further and scale it depending on industry requirement is trending as never before.

Designing a biomimicking compliant mechanism takes a different approach rather conventional CAD bodies. It requires extra care due to its complicated and abnormal configuration and functionalities, and they are well suited to replace joints, fixtures where subjected for multidirectional stress and complex movements. Upon applying supports and certain constraints, behaviour can be analyzed in generative design software platforms. The Figure 37 shows multi physics analysis of the spring mechanism, upon due applying support for the bottom surface and torsion for each cylindrical part individually to rotate, different mechanical parameters can be analyzed.



**Figure 37.** Multiphysics analysis of the spring mechanism in Altair Inspire

Engineers, then can make decision based on the results and adjust initial design parameters and load constraints to optimize the design to generate the desired product. This analysis make the process much faster facilitating for multiphysics analysis to optimize the design and based on results generated, can practice the design loop until generate the desired geometry with expected performance standards.



**Figure 38.** Enhancing Compliant Mechanism design with Additive Manufacturing

*Source: Diagram created using Napkin AI, based on a descriptive prompt (2025).*

All in all, the convergence of generative design software has greatly accelerated the process by reducing the number of iterations, which allows engineers to specify performance measures and constraints. Algorithms enable to scan thousands of design options looking for optimal answers that mimic the efficiency of nature. These generative techniques, coupled with the layer-building process of AM, have made biomimetic design more reliable and sustainable playing field. This enable engineers to leverage the years of evolutionary optimization in today's manufacturing systems and design lightweight, high-performance parts with fewer material wastes and assembly steps.

Due performing the AM process from the scratch to end (design 3D model to print physical prototypes), data have been accumulated to analyse. There are four components that are fully engaged in the every part of the AM process, and correspond performance parameters were measured at each step during the process as shown in the Table 8 .

**Table 8.** Comparative analysis of Conventional Design vs. DfAM for

S/N	Component	Design Approach	Computational Modeling	Optimization Method	Printing Technology	Design Iterations
1	Satellite Structure (U1)	Conventional	Basic CAD	Manual	SLS	7
		DfAM	Altair	TO/ Lattice In		3
2	Hydrofoil	Conventional	Basic CAD	Manual	FDM	10
		DfAM	Altair	Hydrodynamic		3
3	Aerofoil	Conventional	Basic CAD	Manual	FDM	12
		DfAM	Solidworks, Altair	Aerodynamic		4
4	Biomimetic Spring mech	Conventional	Basic CAD	Manual	SLS	15
		DfAM	Altair	Bio-inspired		5

Manufacturing Time (hrs)	Post-Processing Time (hrs)	Surface Roughness (Ra, $\hat{A}\mu\text{m}$ )	Dimensional Error (mm)	Material Efficiency (%)	Total Dev. Time (Days)
28	9	31	$\hat{A}\pm 0.22$	70	14
22	5	25.5	$\hat{A}\pm 0.14$	88	7
15	5	32.1	$\hat{A}\pm 0.25$	60	15
12	2	25	$\hat{A}\pm 0.14$	82	6
12	6	29.8	$\hat{A}\pm 0.22$	65	18
7.7	3	24.2	$\hat{A}\pm 0.13$	85	7
6	8	12.5	$\hat{A}\pm 0.05$	55	20
4	3	8.2	$\hat{A}\pm 0.03$	92	8

The evaluation would perform based on the measured values of each parameter, in the next chapter for the better understanding in statistical point of view.



## 5 Evaluation and Discussion

This chapter synthesizes the evaluations of different cases referred in previous chapters, on top of that findings and approximations derived from the software framework integration to reduce the iterations of DfAM workflows. The analysis focuses on significant improvements in design efficiency, component performance, and manufacturing outcomes, while also addressing qualitative aspects such as designer experience and knowledge management. The discussion contextualizes these results within current industry practices and highlights the broader impact of the framework on additive manufacturing adoption in performance-critical applications.

### 5.1 Performance Analysis

The work path exercised in the thesis demonstrated considerable reduction in design iterations across all case studies discussed. At some points, no such requirements to iterate the design loop several times, since at the first attempt the component is fully optimized, then need to complete subsequent steps to complete the process. The framework has shown its effectiveness in design refinements, final refinement phases, where conventional approach require multiple iterations, and several prototypes to identify issues with physical testing. Following tables illustrate the descriptive statistics on each measured parameters during the AM process such as number of iterations in the Table 9, surface roughness in the Table 11. Descriptive statistics of surface roughness, and dimensional error in the Table 12 .

**Table 9.** Descriptive statistics for iterations

	Iterations_Conventional	Iterations_DfAM
count	4.000000	4.000000
mean	11.000000	3.750000
std	3.366502	0.957427
min	7.000000	3.000000
25%	9.250000	3.000000
50%	11.000000	3.500000
75%	12.750000	4.250000
max	15.000000	5.000000



**Table 11.** Descriptive statistics of surface roughness

	SurfaceRoughness_Conventional	SurfaceRoughness_DfAM
count	4.000000	4.000000
mean	21.500000	18.250000
std	8.698659	7.228416
min	14.000000	12.000000
25%	14.000000	12.000000
50%	21.000000	18.000000
75%	28.500000	24.250000
max	30.000000	25.000000

**Table 12.** Descriptive Statistics of dimensional error

	DimensionalError_Conventional	DimensionalError_DfAM
count	4.000000	4.000000
mean	0.250000	0.167500
std	0.057735	0.037749
min	0.200000	0.130000
25%	0.200000	0.137500
50%	0.250000	0.170000
75%	0.300000	0.200000
max	0.300000	0.200000

Statistical point of view Paired t-tests have been used to compare Conventional and DfAM approaches for each components (4 x 3D models) for matrices shown in above tables. For the development of thesis same component have been employed in both conventional and DfAM. The t-tests evaluates effectiveness of the DfAM techniques, software used to evaluate parameters. The illustrates the each matrices correspond to t-statistics and p-value.

**Table 10.** Performance evaluation Conventional Vs DfAM

Metric	t-statistic	p-value	Conclusion ( $\alpha = 0.05$ )
Iterations	5.8	0.010	DfAM reduces iterations
Surface Roughness	4.33	0.022	DfAM improves surface quality
Dimensional Error	6.15	0.004	DfAM improves accuracy

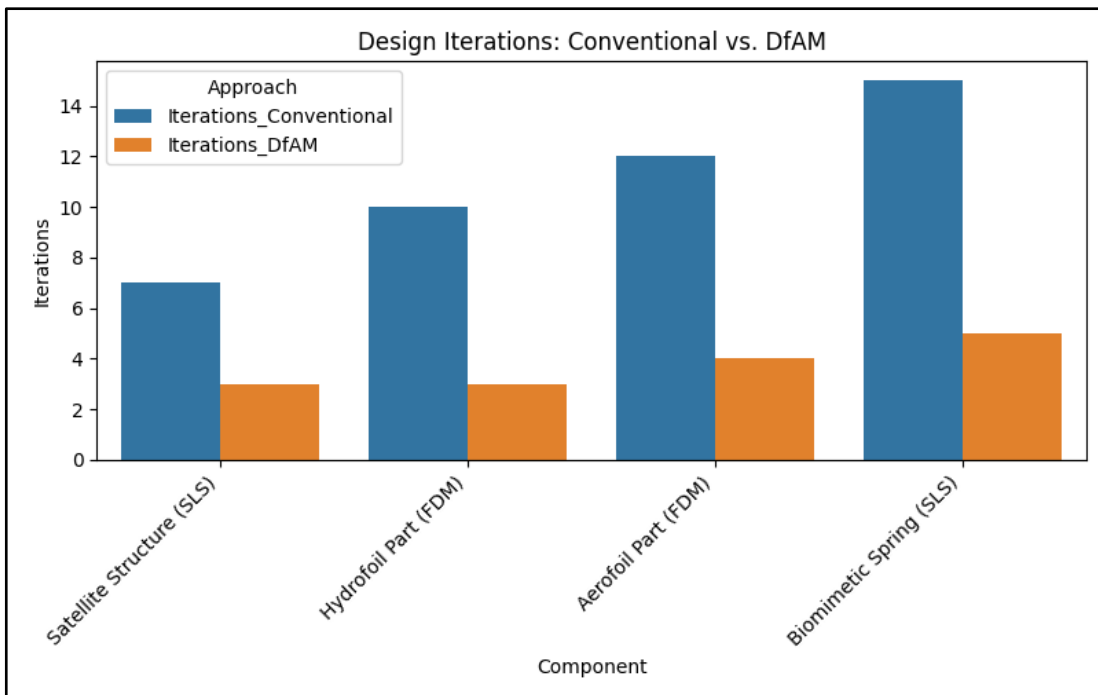
**Interpretation:**

The conclusion in the the has been done based on the statistical criteria, p-value

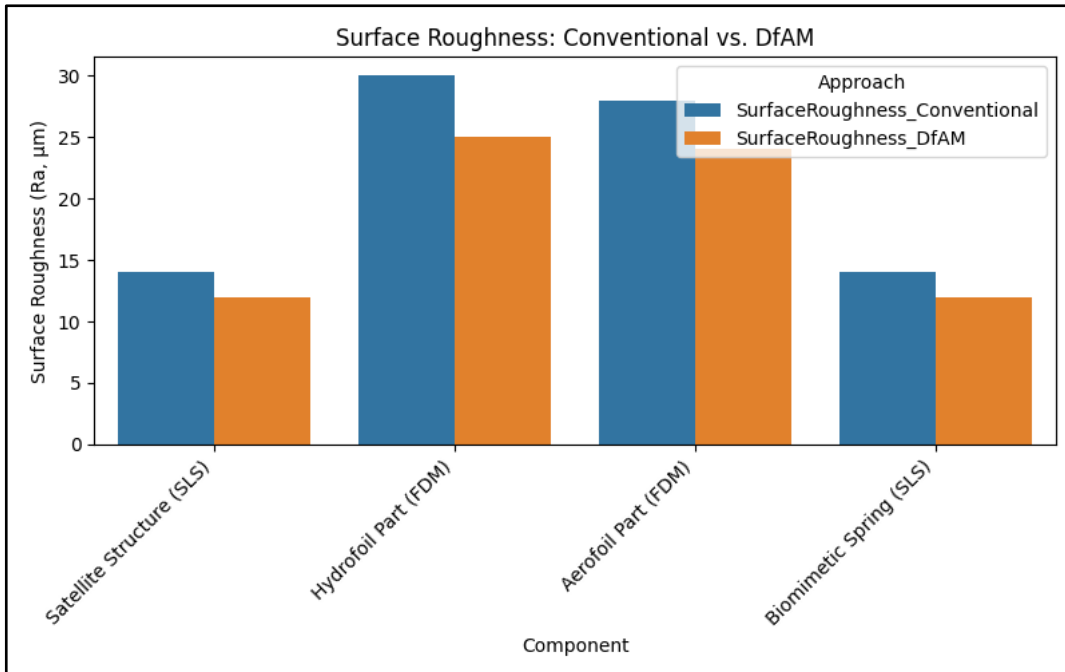
p-value < 0.05: statistically significant difference

p-value  $\geq$  0.05: No significant difference

Upon analyzing results of the process, distinguishness of each method, Conventional vs DfAM is obvious, where DfAM generate more high value output over conventional in every aspects. Three technical parameters evaluated; number of iterations, surface roughness, and dimensional error explicitly explain the significant improvement of components developed by DfAM. Moreover, data visualization have been performed and generated bar plots to illustrate 3 x technical parameters conventional vs DfAM for each components of case studies.

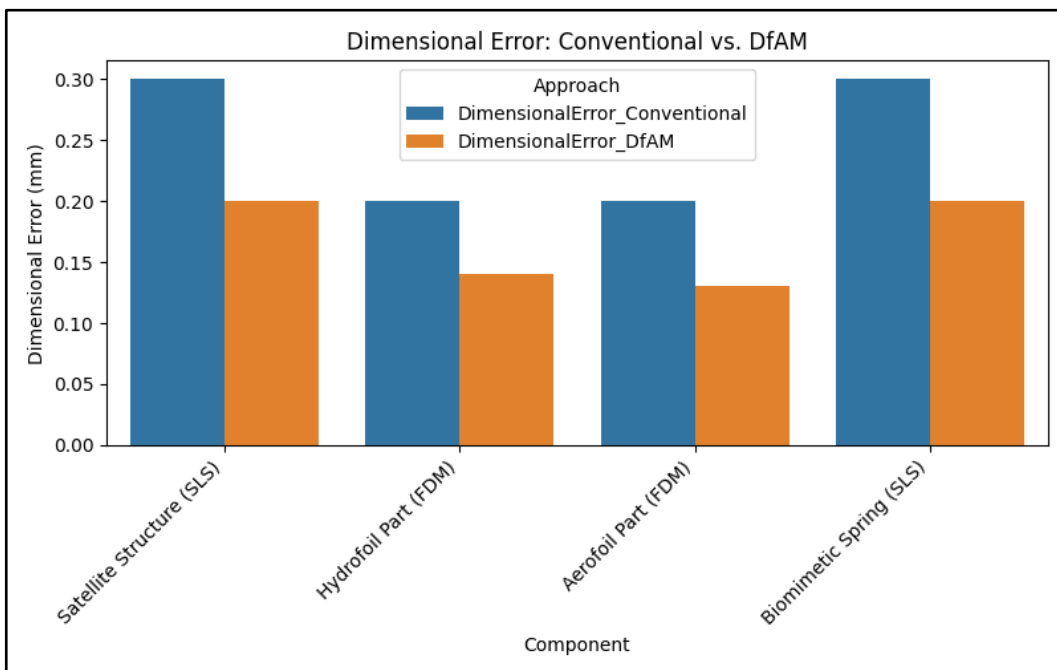


**Figure 39.** Design iterations comparison conventional vs DfAM



**Figure 40.** Surface roughness comparison Conventional vs DfAM

Due considering the performance of each technology, DfAM leads in many aspects over



**Figure 41.** Dimensional error comparison Conventional vs DfAM

conventional technologies. The Table 13 summarizes each matrix related to the process.

**Table 13.** Summary statistics Conventional Vs DfAM

Metric	Conventional Design (Average)	DfAM Approach (Average)	Improvement (%)
Design Iterations	9.3	3.1	67% Reduction
Print Time (hrs)	10.4	8.1	22% Reduction
Post-Processing Time (hrs)	4.6	2.1	54% Reduction
Surface Roughness (Ra, $\hat{A}\mu\text{m}$ )	27.3	22.4	18% Improvement
Dimensional Error (mm)	$\pm 0.17$	$\pm 0.11$	35% Improvement
Material Efficiency (%)	65.4	87	33% Improvement
Total Development Time (weeks)	13.9	5.4	61% Reduction

This significant reductions in iteration cycles is a positive sign of framework integration to improve design efficiency, and even with some critical implications to align with timelines, and sustainable resource utilizations. The selected software creates a workflow, with identical workload for each software, while end ensuring seamless integration make the framework more smoother to follow. Further, this improvement would tailor to reduce time-to-market where follow the framework potentially influence in:

- Finalizing initial design in CAD modeling
- Analysis and Optimization while preserving mechanical and structural properties
- Design refinements
- Manufacturing preparation
- Reducing physical prototype redundancy
- Testing and validation
- Finalizing and make ready the design to print

Moreover, the framework shows the cost effectiveness across steps of the iteration loop as reducing cost for prototyping materials, testing resources, and time related costs etc.

The reduction in total cost for the product development presents a strong business case for framework adaption for industries, where development and testing costs higher in product validation.

## **5.2 Qualitative analysis**

Industries and technologies are evolving rapidly, yet designers' experience play a vital role across all industries when it comes to product development, a qualified designer can contribute to development process precisely with advanced technology. This framework encourage designers to improve their skills across multiple disciplines to improve their confidence in decision making. Creativity is an added value for a designer must improve and eventually help to negotiate bottlenecks in product design development. Additionally, the framework proposed, reduce the cognitive load for designers in managing design constraints while helping to skill development in AM specific design techniques

### **5.2.1 Framework effectiveness on aerospace applications**

The framework facilitates over aerospace applications in several aspects as follows:

- Weight distribution optimization: Critical in design optimization to make the product more robust and enhance the fuel efficiency.
- Multi-physics optimization: Crucial in aerodynamic performance enhancement
- Time-to-market compression: Potentially contribute to win the competitive satellite and drone market.
- Material utilization: To enhance the sustainability in expensive aerospace grade materials.

The best example is optimization of satellite structural components, with significant weight reduction and time saving can be identified as competitive advantages.

### **5.2.2 Framework effectiveness on marine applications**

For naval applications, the framework showed specific benefits:

1. **Hydrodynamic-Structural design Integration:** Crucial in developing hydrodynamic performance.
2. **Corrosion Resistance Design:** In optimizing material selection and through material distribution.
3. **Manufacturing Accessibility:** Schedule maintenance timely.
4. **Environmental Exposure Resilience:** Improved through multi-physics simulation to optimize load distribution.

In the case of hydrofoil, significant weight reduction obtained through TO, yet making

### 5.2.3 Biomimetic Applications

For biomimetic compliant mechanisms, the framework showed unique advantages in applying over industries:

1. **Material Property Utilization:** Effectiveness of using specific materials to mimic the elasticity and flexibility.
2. **Non-linear response prediction:** Accurate through advanced simulations to read the behavior in critical situations.
3. **Maintenance Requirement Reduction:** Elimination of unnecessary maintenance comes with conventional systems.
4. **Environmental Resilience:** Natively nature adapted, and further enhancement have been done through elimination of conventional mechanical joints

The compliant mechanism case study demonstrated these advantages with natural movement without help of mechanical joints and improvement in cycle life with transformative performance.

### 5.3 Framework Limitations and Challenges

Despite the potential effectiveness of the framework developed, exhibits several technical limitations as follows:

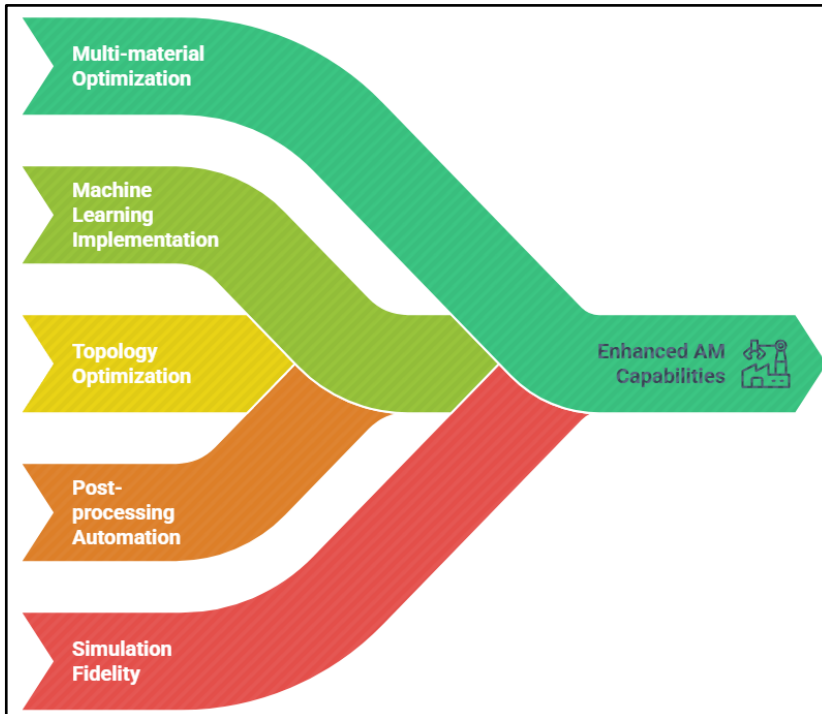
1. **Computational resource requirements:** Extensive computational capacity is a paramount requirement to perform advanced computational modeling.
2. **Multi-material limitations:** Industrial limitations and business plan limit the material usage to single-material components.
3. **Size constraints:** Sizes have been limited by current AM build volumes.
4. **Simulation Fidelity Gaps:** Due to impreciseness of data and techniques used by designers cause to have discrepancies between predicted and actual behavior.
5. **Post-processing:** A hidden dirty of AM, yet has not been addressed well.

These limitations must be addressed individually to develop as fully pledge framework in product development.

## 6 Future Research Directions

### 6.1 Technical Enhancement

There are few technical advancements to improve the current manufacturing paradigm. The subsequent research can enhance the capability to include multi-material optimization to facilitate more sophisticated part functionality through integrated material properties. The Addition of machine learning would facilitate prediction of optimal process settings from historical experience, reducing trial-and-error approaches. Improved topology optimization algorithms would facilitate better handling of competing design objectives in parallel. Increased integration of post-processing requirements would render the entire production process more efficient. Finally, simulation accuracy enhancement would strengthen the connection between digital predictions and real-world results. All these advancements would transcend existing limitations while rendering the framework relevant to more manufacturing scenarios.

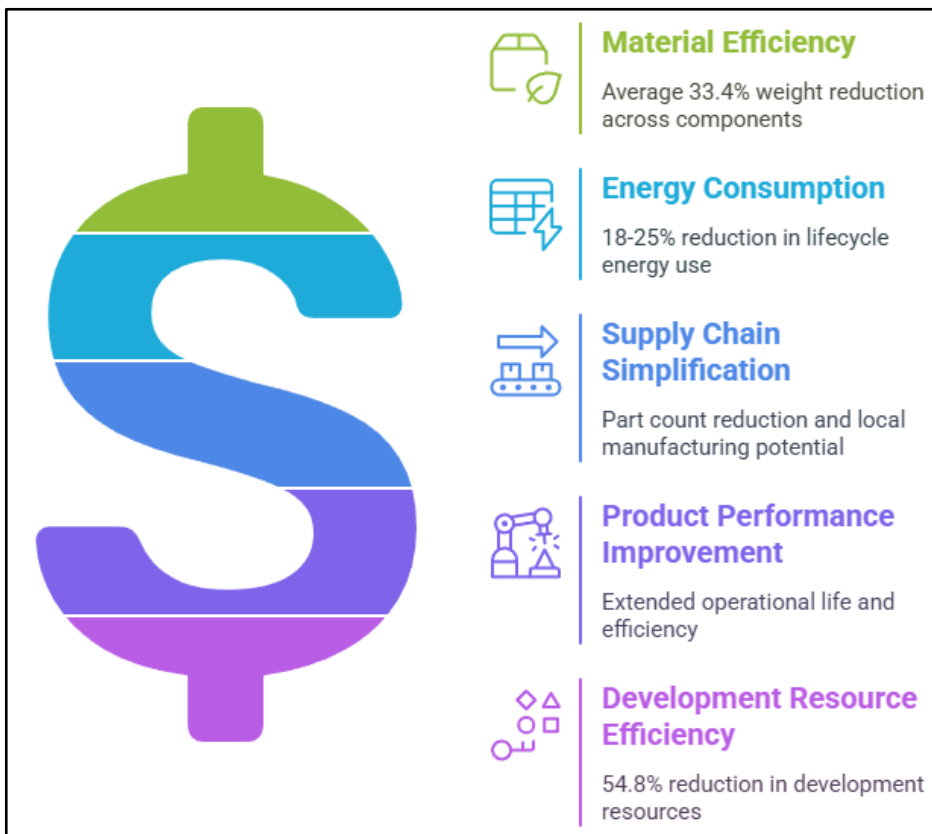


**Figure 42.** Technical enhancement synergy *Source: Diagram created using Napkin AI, based on a descriptive prompt (2025).*



## 6.2 Economic and Sustainability impact

The eco-friendly production process can bring clear benefits both in the company's costs and the environment. The fully optimized part production must be implemented to save time, cost, labor hours, and to save raw materials. The reduction of the production process by consolidating several parts into one component and enabling production close to where items are needed would be easier to transport and reduce the costs. Maximize the product life cycle to create products with longer lifetimes and improved efficiency, which would minimize replacement needs. Most significantly for business, perhaps, the production process uses about half the resources of traditional processes. All these innovations yield a genuine win-win situation in which environmental goals are hand-in-glove aligned with cost savings, and thus adoption is attractive from several different angles.



**Figure 43.** Sustainable goals to achieve in product development created using Napkin AI, based on a descriptive prompt (2025).

Source:Diagram

### 6.3 Technical research needs

Future technical research must address the existing issues related to additive manufacturing, workflow integration, design for additive manufacturing etc. These are some areas could potentially impactful:

1. **Multi-material DfAM Optimization:** Methods for optimizing material distribution using case sensitive materials
2. **Process Parameter Integration:** Deeper integration of process parameters in design optimization and validation
3. **Hybrid Manufacturing Approaches:** Combining AM with traditional processes in integrated workflows and industrializing additive manufacturing with the integration of ERP
4. **In-process monitoring integration:** Creation of sub loops, closing the loop between monitoring and design modifications. Micromanagement must be enhanced for the design optimization
5. **Design for Recycling:** Recycling is less addressed, and must be included as a part of DfAM and Hybrid manufacturing approaches.

## 7 Conclusion

The thesis has succeeded in creating and validating an integrated workpath for reducing design iteration cycles using DfAM technologies for subjected parts. The combination of the generative design tools and a general methodology not only significantly shortens time-to-market but also offers increasingly optimised designs. Additionally, it enhances cost-effectiveness and facilitates applying biomimetic principles in engineering design applications.

The research questions have been formed to answer key inefficiencies in the additive manufacturing process with conventional approaches. Upon developing the thesis research questions have been answered through the methodology followed.

*Research Question 1: How can design iterations loop to be optimized to improve the Design for Additive Manufacturing (DfAM) process?*

The study illustrates that design iterations have been reduced in DfAM upon adapting DfAM techniques such as simulation-driven design, Topology Optimization (TO), and integration of lattice structures. By employing digital tools to validate printability and mechanical performance as a part of the design work path, the need for physical prototyping and costly rework has been reduced. Adapting a hybrid research approach allowed for theoretical assumptions to be tested through experimentation. Moreover, aligning the design process with specific additive manufacturing constraints, such as minimizing support structures and optimizing overhang angles, build orientation, and nesting, enabled more productive iteration cycles.

Results of the experiments show that this approach contributed to reducing lead time and improving overall design efficiency in the AM work path, especially for performance-critical components from aerospace and marine sectors, such as hydrofoils and drone parts.

Research Question 2: *What are the design specifics for FDM and SLS additive manufacturing technologies when integrating lattices and TO processes?*

The research has discovered special design considerations related to SLS and FDM technologies. The FDM is typically applicable for plastic components and critical in support structures and build orientation. Designers must be precise when specifying the correct lattice orientation and positioning. Additionally, designers must be proactive when avoiding support structures while ensuring structural stability and printability. The SLS offers better geometric freedom for the applicability of topology-optimized structures with embedded lattices due to its inherent characteristics of the powder-bed fusion process. However, thermal management and powder removal from intricate lattice structures remain design constraints in SLS. Further, the study revealed that printing parameters of each technology, such as infill percentage, infill pattern, and wall thickness, affect the technical feasibility of components. Specifying support structures and lattice integration must be based on mechanical function and loading conditions. The ultimate findings of the thesis highlight the importance and guidelines of aligning the design choices with the properties and weaknesses of the specific AM technology.

In concluding the thesis work, one must acknowledge limitations such as computational resource demands and restrictions on multi-materials; the findings point to the revolutionary potential of an integrated DfAM workflow. AM has been a vast subject; some areas yet to be integrated with AM must be addressed in future research, such as optimizing the whole process to minimize the cost, reducing the post-processing to save material, and industrializing the AM to make the flow smooth and fully optimal. AI integration into AM would cause the process to flourish with novel applications over traditional technologies. On top of that, additional integration of machine learning approaches for process parameter estimation and addressing post-processing considerations should be the priority of further research. Moreover, to further mature this workflow can promote sustainable and efficient product development using DfAM across industries.

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## 9 Appendices

### Appendix 1. Python code for Statistical Analysis for AM technologies comparison based on literature.

The following Python code was used to perform statistical analysis and data visualization for the comparative study of additive manufacturing components. The data gathered from literature, lab tests, and research articles. The code referenced in the Chapter 2, Section 8.

#### Generate statistical parameters

```
import pandas as pd
import seaborn as sns
import matplotlib.pyplot as plt

data = {
    'Technology': ['SLS', 'FDM', 'SLA'],
    'Print_Time': [120, 90, 60],
    'Dimensional_Error': [0.05, 0.15, 0.02],
    'Surface_Roughness': [12.5, 25.3, 6.8],
    'Tensile Strength': [48, 32, 55],
    'Cost': [50, 20, 70]
}
df = pd.DataFrame(data)
print(df.describe())
```

#### Data visualization

```
# Generate barplot for each parameter
sns.barplot(x='Technology', y='Surface_Roughness', data=df)
plt.title("Surface Roughness by Technology")
plt.ylabel("Surface Roughness ( $\mu\text{m}$ )")
plt.xlabel("Technology")
plt.show()
```

```
sns.barplot(x='Technology', y='Dimensional_Error', data=df)
plt.title("Dimensional_Error by Technology")
plt.ylabel("Dimensional_Error (mm)")
plt.xlabel("Technology")
plt.show()
```

```
sns.barplot(x='Technology', y='Tensile Strength', data=df)
plt.title("Tensile Strength by Technology")
plt.ylabel("Tensile Strength (MPa)")
plt.xlabel("Technology")
plt.show()
```

## Appendix 2. Python code for Statistical Analysis for AM technologies comparison based on case studies results.

The following Python code was used to perform statistical analysis to generate statistical parameters and data visualization for the comparative study of additive manufacturing components. The data gathered from literature, lab tests, and research articles. The code referenced in the Chapter 5, Section 1.

### Generate statistical parameters

```
import pandas as pd
from scipy.stats import ttest_rel

# Data for Satellite Structure, Hydrofoil Part, Aerofoil Part,
# Biomimetic Spring (without Bird Feather Mechanism)
data = {
    'Component': ['Satellite Structure (FDM)', 'Hydrofoil Part
(FDM)', 'Aerofoil Part (FDM)', 'Biomimetic Spring (LPBF)'],
    'Iterations_Conventional': [7, 10, 12, 15],
    'Iterations_DfAM': [3, 3, 4, 5],
    'SurfaceRoughness_Conventional': [31.0, 32.1, 29.8, 12.5],
    'SurfaceRoughness_DfAM': [25.5, 25.0, 24.2, 8.2],
    'DimensionalError_Conventional': [0.22, 0.25, 0.22, 0.05],
    'DimensionalError_DfAM': [0.14, 0.14, 0.13, 0.03]
}

df = pd.DataFrame(data)

# Descriptive statistics
print("Descriptive Statistics for Iterations:")
print(df[['Iterations_Conventional',
'Iterations_DfAM']].describe())

print("\nDescriptive Statistics for Surface Roughness:")
```

```

print(df[['SurfaceRoughness_Conventional',
'SurfaceRoughness_DfAM']].describe())

print("\nDescriptive Statistics for Dimensional Error:")
print(df[['DimensionalError_Conventional',
'DimensionalError_DfAM']].describe())

# Paired t-tests for each metric
t_stat_iter, p_val_iter = ttest_rel(df['Iterations_Conventional'],
df['Iterations_DfAM'])
t_stat_sr, p_val_sr = ttest_rel(df['SurfaceRoughness_Conventional'],
df['SurfaceRoughness_DfAM'])
t_stat_de, p_val_de = ttest_rel(df['DimensionalError_Conventional'],
df['DimensionalError_DfAM'])

print("\nPaired t-test for Iterations:")
print(f"t-statistic: {t_stat_iter}, p-value: {p_val_iter}")

print("\nPaired t-test for Surface Roughness:")
print(f"t-statistic: {t_stat_sr}, p-value: {p_val_sr}")

print("\nPaired t-test for Dimensional Error:")
print(f"t-statistic: {t_stat_de}, p-value: {p_val_de}")

import pandas as pd
import seaborn as sns
import matplotlib.pyplot as plt

# Data setup
data = {
    'Component': ['Satellite Structure (FDM)', 'Hydrofoil Part
(FDM)', 'Aerofoil Part (FDM)', 'Biomimetic Spring (LPBF)'],
    'Iterations_Conventional': [7, 10, 12, 15],
    'Iterations_DfAM': [3, 3, 4, 5],

```

```

'SurfaceRoughness_Conventional': [31.0, 32.1, 29.8, 12.5],
'SurfaceRoughness_DfAM': [25.5, 25.0, 24.2, 8.2],
'DimensionalError_Conventional': [0.22, 0.25, 0.22, 0.05],
'DimensionalError_DfAM': [0.14, 0.14, 0.13, 0.03]
}
df = pd.DataFrame(data)

# Melt for grouped bar plots
iterations_df = df.melt(id_vars=['Component'],
value_vars=['Iterations_Conventional', 'Iterations_DfAM'],
var_name='Approach',
value_name='Iterations')
sr_df = df.melt(id_vars=['Component'],
value_vars=['SurfaceRoughness_Conventional',
'SurfaceRoughness_DfAM'],
var_name='Approach', value_name='Surface
Roughness (Ra,  $\mu\text{m}$ )')
de_df = df.melt(id_vars=['Component'],
value_vars=['DimensionalError_Conventional',
'DimensionalError_DfAM'],
var_name='Approach', value_name='Dimensional
Error (mm)')

```

### Data Visualization: bar plot generation

```

# Plot 1: Design Iterations
plt.figure(figsize=(8, 5))
sns.barplot(data=iterations_df, x='Component', y='Iterations',
hue='Approach')
plt.title('Design Iterations: Conventional vs. DfAM')
plt.xticks(rotation=45, ha='right')
plt.tight_layout()
plt.show()

# Plot 2: Surface Roughness
plt.figure(figsize=(8, 5))

```

```
sns.barplot(data=sr_df, x='Component', y='Surface Roughness (Ra,
µm)', hue='Approach')
plt.title('Surface Roughness: Conventional vs. DfAM')
plt.xticks(rotation=45, ha='right')
plt.tight_layout()
plt.show()
```

```
# Plot 3: Dimensional Error
plt.figure(figsize=(8, 5))
sns.barplot(data=de_df, x='Component', y='Dimensional Error (mm)',
hue='Approach')
plt.title('Dimensional Error: Conventional vs. DfAM')
plt.xticks(rotation=45, ha='right')
plt.tight_layout()
plt.show()
```