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Investigating the design workflow for designing a component for Additive Manufacturing

A case study of designing a jet engine combustion chamber component for AM

School of Technology and Innovation
Master's thesis in Industrial Systems Analytics

Vaasa 2020

UNIVERSITY OF VAASA
School of Innovation and Technology
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Title of the Thesis: Investigating the design workflow for designing a component for Additive Manufacturing: A case study of designing a jet engine combustion chamber component for AM
Degree: Master of Science
Programme: Industrial Systems Analytics
Supervisor: Rayko Toshev
Year: 2020 **Number of pages:** 123

ABSTRACT:

The increasing integration of Additive Manufacturing (AM) in the Product Development and production phase has brought a need for developing a new design for manufacturing methodology which is distinct to AM. Commonly known as Design for Additive Manufacturing (DfAM), it aims to take complete advantage of the unique capabilities of AM by developing rules, guidelines, and design methodologies. The existing studies on DfAM do not address practical problems faced during the design stage which leads to dilemmas and uncertainties in decision making concerning the design elements. Therefore, a workflow for implementing the methodologies of DfAM is important. To solve this problem, this thesis develops and documents the workflow for modeling lattice structures and minimal structures using the best tools available. In addition to this, the study analyzes the workflow developed with the help of a case study. In this case study, a component is developed for heat management which makes the use of heat transfer between solid and fluid. The design process in the case study is developed with the integration of Design for Six Sigma methodology. The outcomes are documented, and best practices from the study are reported.

KEYWORDS: Design for Additive Manufacturing, DfAM, Additive Manufacturing, Design for Six-Sigma, DFSS, Conjugate Heat transfer Analysis, Lattice Structures, Minimal Structures, Gyroid Structures, Siemens NX, nTop Platform

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Abbreviations

AHP	- Analytic Hierarchy Process
AM	- Additive Manufacturing
BJ	- Binder Jetting
CAD	- Computer Aided Design
CAE	- Computer Aided Design
CHT	- Conjugate Heat Transfer
CTS	- Critical to Satisfaction
DfAM	- Design for Additive Manufacturing
DFSS	- Design for Six Sigma
ISO	- International Organization for Standardization
LSS	- Lean Six Sigma
ME	- Material Extrusion
MJ	- Material Jetting
NX	- Siemens NX
PBF – M	- Powder Bed Fusion (Metal)
PBF – P	- Powder Bed Fusion (Polymer)
TPMS	- Triply periodic minimal surfaces
VOC	- Voice of Customer
VP	- VAT Polymerization

Acknowledgment

I would like to thank Dr. Rayko Toshev for his motivation, guidance, and encouragement throughout my graduate career. I am grateful to have him as my thesis supervisor. This thesis is part of my research on Additive Manufacturing at the University of Vaasa under his supervision. I would also like to thank Mr. Heikki J Salminen, for his support on the technical know-how of the case study and supervision of the computer simulation in this thesis.

A heartfelt thanks and gratitude to my late father, my family, and friends for their continuous support and motivation during my hard times.

1 Introduction

According to ISO Standards (ISO/ASTM-52900, 2017), the definition of Additive Manufacturing (AM) is “Manufacturing processes which employ an additive technique whereby successive layers or units are built up to form a model.” AM is also known under the terms such as 3d printing, free-form manufacturing, desktop manufacturing. An article by Terry et al (Gornet, 2017) claims that 3D systems in 1987 introduced Stereolithography Apparatus which prints by solidifying thin layers of light sensitivity (Ultraviolet) liquid polymers using lasers. However, the technology was patented and was released to the public only after 2006 (Hull, 1984). Since then the technology has been continuously innovated, and new printing methods like Fused Deposition Modelling (FDM), Selective Laser Sintering (SLM), and Laminated Object Manufacturing (LOM) were developed. Reference to (Dancel, 2019) indicates that the AM technology's mass adoption trend is due to a rise in the affordability of 3D printers. Industrial manufacturing is gearing up for the Industrial Revolution 4.0, the manufacturing system with increased integration of Digital Systems, Automation, and Robotics (Liao et al., 2017). In addition to this, the Industrial Revolution 4.0 paves way for flexible and smart manufacturing where 3D printers play a major role in increasing productivity and ease of adaptability for change in manufacturing. Furthermore, this technology allows rapid prototyping and completion of the product development phase in a shorter period. For product-based companies, in a competitive environment, success depends on how quickly the company can innovate a product and attract the consumers (Mohr et al., 2010). Innovation requires product development and rapid prototyping methods which are cheaper and faster. Hence AM is gaining importance in the product development and manufacturing phase (Lindwall et al., 2017). The designs for manufacturing for conventional manufacturing are not completely applicable to AM (Wohlers, 2005). Hence, this opens up a need for developing a new set of design principles and workflows for AM commonly known as Design for Additive Manufacturing (DfAM). The complete realization of advantages and manufacturing capabilities of AM can only be achieved when its fullest potential is understood and utilized accordingly. Let us consider Topology optimization (TO), the technique of computer simulation which allows reducing the mass without compromising the strength (Bendsoe & Sigmund, 2013). TO generates results which are extremely complicated in terms of geometries and shapes. As a result, AM goes hand in hand with TO because of its ability to manufacture complex geometries and shapes. However, if the geometries are not self-supporting, the print will fail; thus, support structures must be generated for both physical support and in case of metal AM to enhance heat dissipation. Removal of support structures are sometimes complicated and can cost a significant share of total print costs (Jiang & Xu, 2018). Hence, DfAM plays an important role in designing for AM. DfAM consists of rules for designing and manufacturing in AM (Kumke et al., 2016b), which is key for utilizing the potential of AM to its fullest.

The sheer difference between the conventional (subtractive and formative) manufacturing and Additive Manufacturing (AM) method in terms of how the product is being manufactured, differentiates the design process followed in designing components for manufacturing. Therefore, mechanical designers with experiences in conventional manufacturing methods are required to learn the design principles of AM. For instance, while conducting Finite Element Simulations (FEM) simulations; due to less complexity of the geometries of products manufactured by conventional manufacturing, the meshing and simulation process is faster. On the other hand, the unique feature of the AM is its ability to manufacture complex geometries (D. W. Rosen, 2016). And so, the meshing and conducting simulations will be comparatively complicated and will consume more time and resources. The application of DfAM methodology in the design process needs to be studied in-depth and developing a dedicated workflow is essential. This study introduces the readers to design principles of AM, discusses existing research on DfAM, describes the methodology in designing the shapes AM, and with a case study, aims to develop a workflow ideal for DfAM. In addition to this, the design process needs to track the data of different parameters involved in DfAM. By implementing the Design for Six Sigma methodology, this research aims to streamline the use of parameters in the design process.

1.1 Research Area

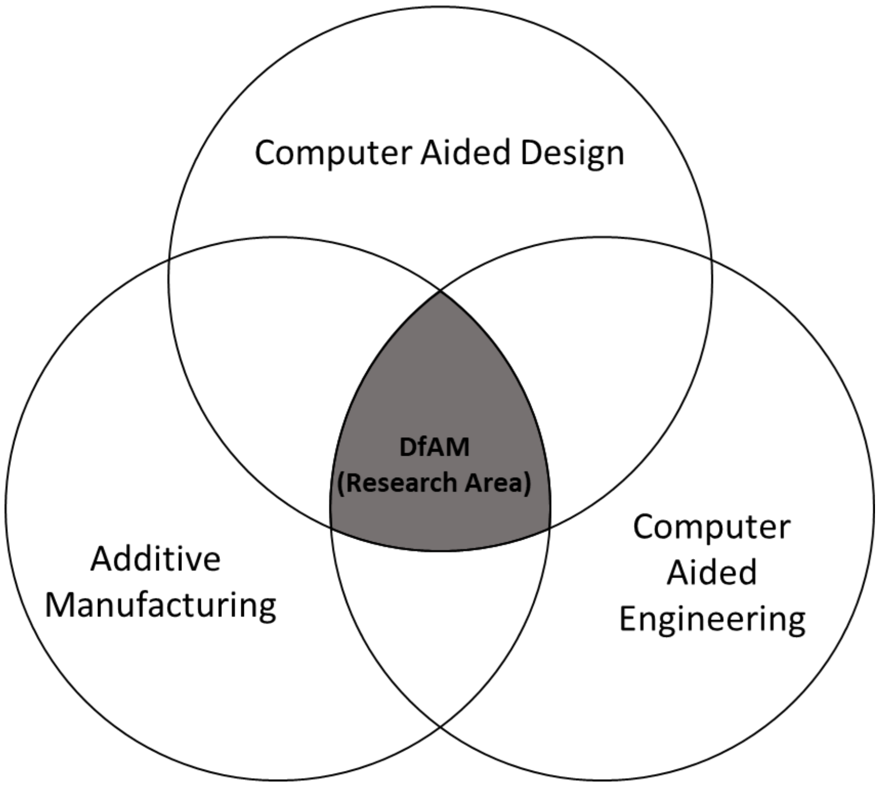


Figure 1 Research Area in a Venn Diagram

The research area of this thesis focuses on Design for Additive Manufacturing (DfAM), which includes the study on principles of Additive Manufacturing (AM), Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE). The introduction and growth of AM in conventional manufacturing set up have opened up space for a newer area for research and development commonly known as Design for Additive Manufacturing (DfAM). DfAM focuses on improving the manufacturability of the design, considering the capability of the AM, and bringing down the overall cost. However, there have been only a few studies that concentrate on the workflow of Integrating DfAM, CAD, and CAE. The importance of an integrated study is to help the designers and industries understand the changes required in the workflow for approaching the DFAM. Thus, this study explores the different workflows, their advantages, and disadvantages and suggests the best practices by considering a case study of designing a heat management solution to be used in a jet engine application. To standardize the design process, the thesis follows the Design for Six Sigma approach.

To minimize the complexity involved and reduce the project span, the study only focuses on the design and validation, and does not include,

1. Structural load study.
2. Manufacturing of the final design.

The key highlight in the research include the following,

- Exploring the workflow for designing Lattice structures like cellular lattices.
- Studying the workflow for designing minimal surfaces like Gyroid.
- Evaluating the workflow for Conjugate Heat transfer analysis of the lattice structures.
- Integration of Design for Six Sigma tools in the design workflow.

1.2 Research Onion as a Framework

Saunders's Research onion is a systematic and detailed approach for presenting the research process adopted in a research paper (Mark et al., 2007). As illustrated in Figure 2, the Research Onion is studied from the outermost layer and to the innermost layer. Each layer represents a detailed description of the respective stages in the research process. In the following paragraphs, an attempt is made to introduce the readers to the methodologies and philosophies embraced in the research process of this thesis.

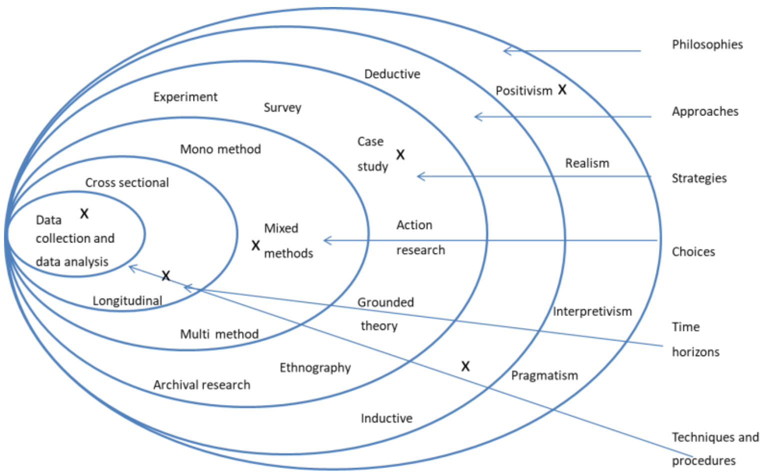


Figure 2 Saunders's Research onion, (Mark et al., 2007)

Research Philosophy (Layer 1)

The research philosophy of this study leans on Epistemology. According to (Bryman, 2016), Epistemology incorporates positivism, realism, and interpretivism. The philosophy of the study chosen in this thesis is Positivism. The underlying motivation for the study is the questions that needed to be answered. With the increasing integration of Additive Manufacturing, due to simpler and more affordable machines in the market, the research questions framed are intended to help the mechanical designers and researchers in the field to understand how they can use existing designing approaches to design objects for AM. An effort was made to answer the questions in a very scientific manner with evidence that supports the claims made in the discussion.

Research Approaches (Layer 2)

The research approaches layer in Saunders's Research onion concerns with the validation of the facts and findings of the research. In their book (Mark et al., 2007) describes that the research approaches can be of two types; namely, deductive and inductive approaches. According to (Silverman, 2013), the deductive approach develops a theory or hypothesis (or hypotheses) on existing theory and then frames the research approach to test it. On the other hand, as per (Bell et al., 2018) the Inductive approach is described as a move from a specific area to general of the research topic. The research approach in this thesis can be characterized as a Deductive approach. There are pre-existing studies on the implementation of Design for Additive Manufacturing describing its purpose and benefits. This research focuses on the existing studies and evaluates the approach to answer the questions considering a case study.

Research Strategies (Layer 3)

Research Strategies describes the strategies used by the researcher to carry out the research work (Mark et al., 2007). These strategies, in general, include a number of different approaches, namely case studies, interviews, surveys, archival research, etcetera. The strategy of the research work in this study is carried out by case study research. After establishing the groundwork for the design principles and methodologies in additive manufacturing as well as general industrial design; the research proceeds to implement it in a case study to arrive at a conclusion that can assess the findings from the case study and answer the research question.

Research Choices (Layer 4)

Research Choices describes the choice of methodology in the collection and processing of the data. There are three choices used in research, mono-method, mixed-method, and multi-method. These methods are differentiated by the approach of adopting the qualitative and quantitative methodology. The research choice made in this study is multi-methods. Both qualitative and quantitative methodologies are used to answer the research questions.

Time Horizon (Layer 5)

This layer provides information about the time dependency of the research work. There are two types of Time Horizons in research, namely cross-section and longitudinal (Bryman, 2016). The cross-sectional time horizon focuses on collecting data from a specific time whereas the longitudinal time horizon collects data repeatedly from an extended time period. The research in this study collects data over a cross-sectional time horizon. The data collected to support the conclusion are mainly from the design workflow and simulations associated with the case study.

Data Collection Methods (Layer 6)

This is the innermost layer of the Research onion. The data collected are from both the primary source and secondary source. The primary source mainly consists of the data collected from the simulations and design process of the case study. The secondary data are the design procedures, parameters, and literature from various sources including research papers, books, YouTube tutorials, and blogs.

1.3 Research Questions

1) What is the optimal workflow for designing a metal component for heat transfer produced by Additive Manufacturing technology?
2) What are the challenges faced by the designers while designing for AM in terms of the current software capabilities?
3) Can lattice structures with complex geometries be designed by conventional CAD software?
4) Can lattice structures be simulated for thermal properties using conventional computational software?

1.4 Case study Problem Statement

The model shown below is a hypothetical combustion chamber geometry. The region marked red is the region where combustion takes place and produces 35400 Watts of heat.

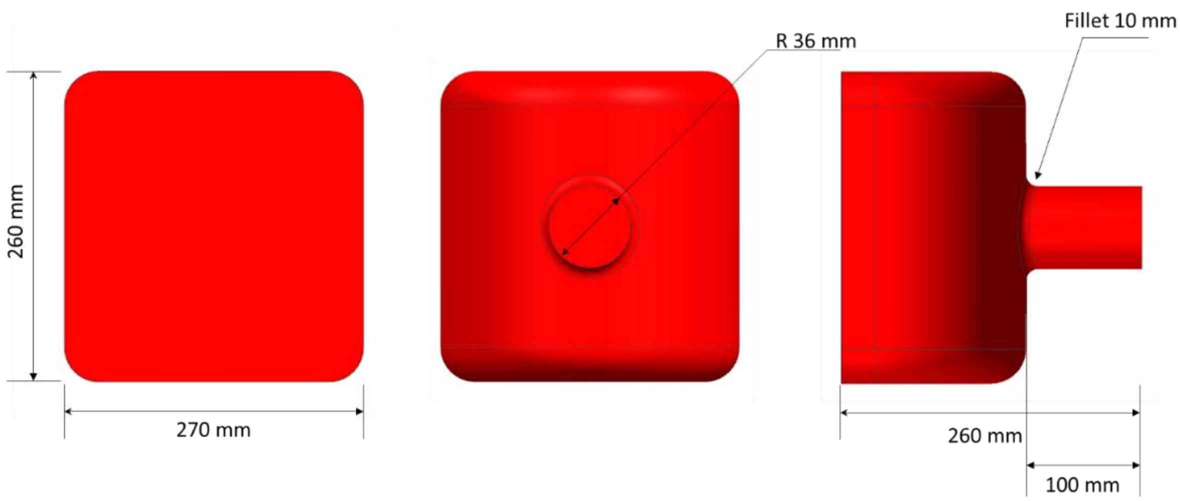
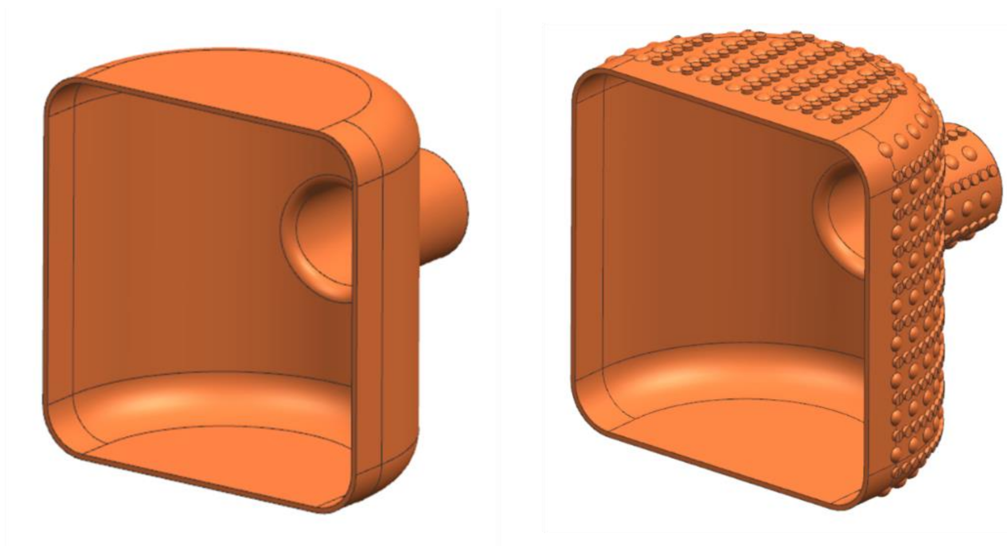


Figure 3 Combustion geometry and dimension

The objective of the design challenge is to model structures for heat management with minimum exergy loss. The end goal is to maintain the wall temperature in the above model below 590 c and to achieve that. A 4mm thick wall is built around the geometry, which can resist the pressure load inside the combustion chamber geometry.

To cool down the geometry, compressed air is used as a coolant under an inlet pressure of range of 82- 81 bar with expected pressure at the outlet at 80 bar. The temperature range of coolant is 300 - 500 c near the inlet region. The channel for coolant flow can be increased to a height of 4 mm. To increase convection and thereby to facilitate more heat transfer, designs with the higher surface area are preferred. The cooling features are mapped conformally over the wall to facilitate even distribution of temperature near the inner surface of the wall.

The Figure 4 shows the design options,



4 mm wall without structures to facilitate cooling

4 mm wall with structures to facilitate cooling

Figure 4 Wall around the geometry and conformal cooling channel

The secondary objective of the challenge is to obtain maximum material utilization efficiency while maintaining minimum mass. The possible structures could be the use of lattice structures or pin fins but avoid using slender cross-sections. Figure 5 represents an example of the final model expectation. The boundary conditions for conjugate heat transfer simulations are,

Coolant material: Compressed Air with a density of 56,2 kg m^{-3}

Inlet pressure: 81-82 bar in 1 bar steps (can be increased up to 81 bar)

Inlet temperature: 300- 500 c in 100 c steps

Outlet Pressure: 80 bar

Heat flow near the combustion chamber wall: 35.4 kW

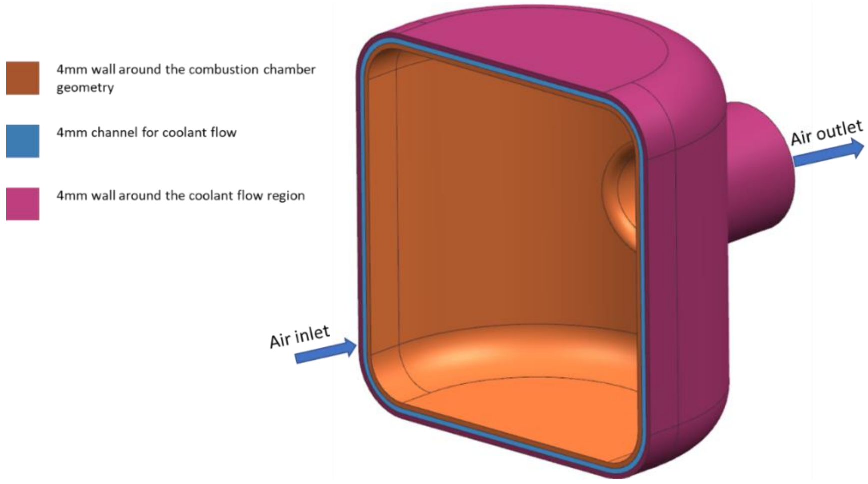
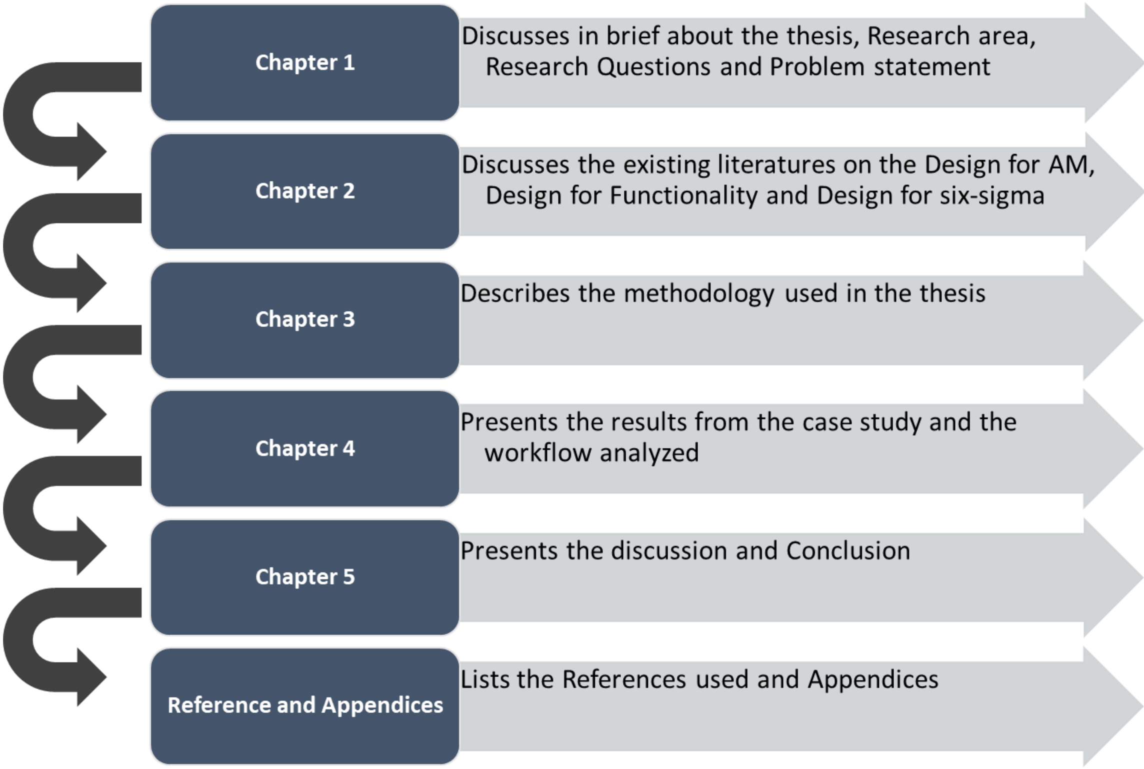


Figure 5 Design example

1.5 Structure of the Study

This study is structured into 5 chapters. Chapter 1 introduces the readers to background information, research questions, and case study of the problem statement. Chapter two discusses the existing study on the topics essential for understanding the thesis. These include literature reviews of researches on topics such as AM, DfAM, CAD, and CAE. Chapter 3 describes the methodology used in the study. The results from the investigation of the workflow associated with the designing and conducting simulation for the case study component is presented in Chapter 4. Chapter 5 presents the conclusion by answering the research questions, discusses the outcomes from the study, and suggests the scope for future study.



2 Literature Review

2.1 Additive Manufacturing

Additive Manufacturing (AM) is described by (Diegel et al., 2019) as the process of making a three-dimensional solid body layer by layer of virtually any shape from a digital model. The term additive refers to the process of manufacturing where the material is added layer by layer (Gebhardt & Hötter, 2016). The unique characteristics of AM are its ability to manufacture intricate and complex geometry with near-zero waste material and minimum post-processing (Bikas et al., 2016). These characteristics enabled AM to be promising and get introduced in the conventional manufacturing environment. According to the Wohlers Report, the AM industry had 33.5 percent growth in 2018 and forecast revenue of 40.8 B USD for 2024 (Haarburger et al., 2019; Inc., 2020). The AM technologies can be classified as shown in Figure 6 (Redwood et al., 2017).

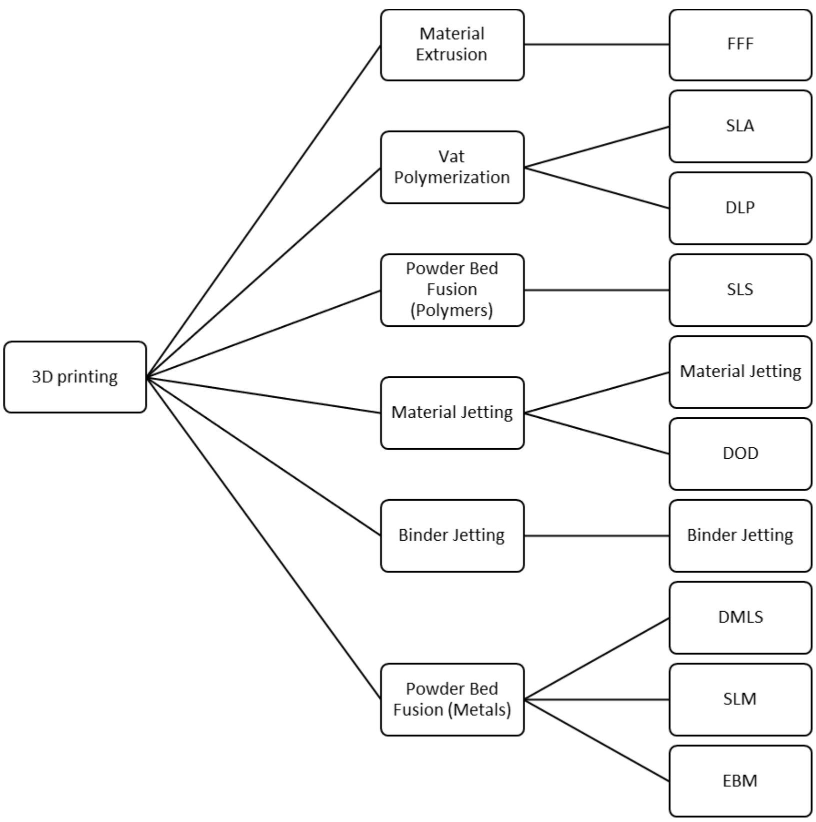


Figure 6 Additive Manufacturing Process Classifications.

2.1.1 **Additive Manufacturing Processes**

Material Extrusion (ME):

The printing process in the Material Extrusion is by pushing a string of solid thermoplastic filament through a hot nozzle, melting it, and depositing it over a build platform (Redwood et al., 2017). The most common technologies working on material extrusion are Fused Filament Fabrication (FFF) and Fused Deposition Modeling (FDM) (Gonzalez-Gutierrez et al., 2018). The equipment used for ME is typically inexpensive and a wide variety of materials are available. Other characteristics include low accuracy, rougher surfaces, anisotropy properties, and typically require support structures (Turner et al., 2014).

VAT Polymerization (VP):

The printing process in the VAT Polymerization (VP) is by curing polymer resin using a light source which is typically Laser (Redwood et al., 2017). The most common technologies working on VP are Stereolithographic apparatus (SLA™), Digital light processing (DLP™), Scan, spin, and selectively photocure (3SP™) and Continuous liquid interface production (CLIP™) (Diegel et al., 2019). The major strengths of this process are High level of complexity and accuracy and smooth surface finish. The weaknesses of the process are the material used can only be photo-resins, expensive equipment, and material creeping after curing (Gonzalez-Gutierrez et al., 2018).

Powder Bed Fusion (Polymers and Metal) (PBF):

The printing process in the Powder Bed Fusion (Polymers) (PDF – F) is by inducing fusion between powder particles at a specific location of the build area with a help of thermal source and then solidifying the part (Redwood et al., 2017). The common technologies in this process are Selective laser sintering (SLS™), Direct metal laser sintering (DMLS™), Electron beam melting (EBM™), Selective heat sintering (SHS™), Multi-jet fusion (MJF™), HP Jet fusion™ and High-speed sintering (Diegel et al., 2019). Typical materials are Plastics, Ceramics, and Metals. The key characteristics of this process are the complexity of the operation, expensive equipment, materials can age/oxidize, no supports required (powder acts as support), and the requirement of post-processing (Gonzalez-Gutierrez et al., 2018).

Material Jetting (MJ):

The printing process in the Material Jetting (MJ) is done by jetting thermoset photopolymer resins in tiny droplets are then using UV light to cure them (Redwood et al., 2017). The common printing technologies working on the MJ principles are Polyjet^{TM} Smooth curvatures printing (SCP^{TM}), Multi-jet modeling (MJM^{TM}), and Drop on Demand (DOD) (Gonzalez-Gutierrez et al., 2018). The characteristics of MJ are very good accuracy, multi-material parts can be printed, a limited number of materials available and allows printing full-color parts (Gibson et al., 2015). The common printing materials are Photopolymers, waxes, composites, and thermoplastic polymers.

Binder Jetting (BJ):

The printing process in the Binder Jetting (BJ) is done by the process of depositing binding agents onto a powder bed layer by layer and forming a part (Redwood et al., 2017). The common printing technologies in BJ are 3D printing (3DP^{TM}), ExOne, and VoxelJet (Diegel et al., 2019). The typical materials include metals, plastics, glass, and ceramics. The characteristics of the BJ process are the requirement of post-processing, a wide range of material, the printing of full color is allowed, properties are dependent on the binder used, high productivity, and powders can be harmful (Du, 2017; Gonzalez-Gutierrez et al., 2018).

2.2 Design for Additive Manufacturing (DfAM)

According to (Laverne et al., 2014), Design for Additive Manufacturing (DfAM) is a set of methodology, principles, and tools that helps the mechanical designers to take into consideration the specific requirements of the AM during the product design stage. One of the distinguishable features of the AM compared to conventional manufacturing processes like Subtractive and Formative is the end product is built layer by layer material deposition (Langelaar, 2016; Tofail et al., 2018). This requires certain design considerations while designing for AM to maximize the use of the capabilities of AM in a very economic and feasible way. Therefore, this leaves a major knowledge gap between a designer of components for conventional manufacturing and a designer of components for AM (Morski, 2016; Pradel et al., 2018a). With the increase in large scale commercial application of AM, DfAM needs to become well established amongst the mechanical designers and industries to make use of the full potential of AM (Mehrpouya et al., 2019).

Past studies by (Kumke et al., 2016a) have categorized DfAM into two classifications, namely DfAM for design decisions and DfAM for Manufacturing potentials. The DfAM for design decisions focuses on design specifications such as best practices, rules, and guidelines (Kumke et al., 2016a). Hence, the conventional designer must learn the design principles of AM before designing for AM. The design principles may vary between the type of AM machines, although the main principles governing the manufacturability are the same throughout different AM manufacturing methods (Valjak & Bojčetić, 2019). The DfAM for manufacturing potentials focuses on the activities concerning the manufacturing, this includes the choice of AM process, pre-processing activities, and post-processing (Kumke et al., 2016a). That is when the product is taken out of the AM machine, whether it might undergo post-processing to get the required surface finish, accuracy, or strength. The post-processing is usually job or application dependent (Redwood et al., 2017). Therefore, it is quite essential to find and provide the required allowances for the product to meet the requirements.

In this thesis, the AM manufacturing method of Powder Bed Fusion – Metals (PBF-M) is considered as the manufacturing method for the design solution. Hence, the design principles surrounding the (PBF-M) will be discussed in the following paragraphs, and it must be noted that the general principles of all the AM processes are similar.

2.2.1 **Design for better Accuracy and Surface finish**

In the (PBF-M) printing process, the laser beams melt the powder and build up the shape layer by layer (Gardan, 2016). During this process, the geometrical accuracy and the surface finish lies within the range of grain size of the powder being used for the printing job (Diegel et al., 2019). Therefore, tolerances are required to be provided during the design stage. The surface finish of the end product varies depending upon the build orientation of the printed product, this is due to the layer-wise building (Taufik & Jain, 2014). If the face of the printed object is parallel to the layer, the chances of getting a smooth finish are higher. According to (Redwood et al., 2017), the quality of the printed surfaces increases as the angle of overhanging features is less than 45 °. Furthermore from the study by (Charles et al., 2019), it can be noted that it would be better to minimize the downfacing and tilted surfaces while designing for AM. As a Design engineer for AM, knowing the range of roughness that can be obtained by the printing process helps in designing the component to avoid unintended roughness which affects the performance of the component and requirement of the customer.

2.2.2 **Design for optimal Mechanical shapes**

Engineering drawings and designs are generally composed of mechanical shapes made of different geometries put together to make a shape such as gears or holes. In general, additive manufacturing of the mechanical shapes that are placed vertically is of better quality compared to that of horizontally placed objects (Saunders, 2017).

2.2.3 **Self-supporting structures:**

In additive manufacturing, the structures which do not require external supports during the printing process are called Self-supporting structures. These structures are generally below 45 degrees inclined when the print object is placed perpendicular to the printing direction (Langelaar, 2016). The main consideration is to be given when designing lattice structures or beams that are placed at an angle. One key design feature would be to include fillets near the joints to improve the printing (Redwood et al., 2017). Self-support structures also minimize the generation of support structures which are required to be removed during the post-processing of the print (Jiang & Xu, 2018). Lesser the support material, lesser is the time consumed for post-processing, and print quality would be better. Support structures can also improve print quality, but the strategy must be so that the support structures are only used in the required places. For (PBF-M) process support structures are required for the following functions (Jiang & Xu, 2018),

- For thermal dissipations
- For printability
- For part balance

2.2.4 **Print orientation/Avoid anisotropy**

Anisotropy is nothing but the difference in mechanical properties in the vertical direction from the base to top. This is due to layer-wise printing my method of AM, hence print directions play a major role (Kok et al., 2018) in avoiding the anisotropy. Although, this defect is commonly found in the material extrusion method compared to the metal powder bed fusion method of printing. In the case of MS printing, this can be eliminated using Hot Isostatic Pressing (HIP) (Wu & Lai, 2016). Therefore, the design engineer needs to consider the importance of orientation while designing the component, so the minimum number of features that are subjected to forces weaker sections due to anisotropy.

2.2.5 **Holes and Round sections/Passages**

The orientation chosen while printing the objects with cross-sections like holes and round sections/passages play a vital role in determining the print quality as well as the accuracy (Redwood et al., 2017). In the SLM printing process, due to the unavailability of support structure inside a circular cross-section, there is a tendency that the topmost part will have a sagging structure (Redwood et al., 2017). To avoid this kind of deformity, a tear-shaped cross-section should be preferred instead of a circular cross-section (Schmelzle et al., 2015).

2.2.6 **Design for minimum post-processing**

In additive manufacturing, the major share of the total cost required for manufacturing a component is allocated to post-processing. The post-processing may be heat treatment for decreasing thermal stress (or thermal load or anisotropy) or subtractive machining like milling or surface finishing (Kumbhar & Mulay, 2018). The design strategies, as well as considerations taken in the initial stages of design, can help in reducing the cost incurred in post-processing. The overall design considerations or thought process that can be implemented during the design process are as follows (Diegel et al., 2019),

- ✓ Consider the right print orientation
- ✓ Consider replacing temporary supports with permanent walls
- ✓ Consider changing angles of features requiring support
- ✓ Consolidate several parts into the single part without compromising the functions.

2.2.7 **Optimize the part using topology optimization**

One of the key advantages of additive manufacturing is it allows manufacturing components with complex geometries (Bikas et al., 2016). Topology Optimization is a numerical method that optimizes material layout in a given design space for a given boundary condition without compromising the required performance targets (Bendsoe & Sigmund, 2013).

The general workflow for topology optimization is as follows,

1. Simplify the model
2. Define design space
3. Apply boundary conditions and materials
4. Set up the scenario
5. Perform topology optimization
6. Convert the results to a smooth body

In theory with the design criteria provided during the topology optimization, the resultant body can be manufactured using traditional manufacturing methods. But when the design shapes become complex the manufacturing becomes expensive and infeasible. Therefore, additive manufacturing is considered the most suitable method of manufacturing for topology optimized structures or bodies (Diegel et al., 2019).

2.2.8 **Design for lightweight structures**

A design engineer while working on structural design aims to achieve maximum structural strength with maximizing mass efficiency (Ramalingam, 2008). Therefore, lightweight structures are always preferred while designing the CAD model of the design. For example, while designing structures for aerospace application the engineering features such as high strength to weight ratio, high resilience per weight ratio are given maximum preference. As well as lesser material utilization attributes to more economical and environmental benefits (Seepersad, 2014). The AM design allows a designer to maximize design for functionality which is driven by engineering specification instead of manufacturing ability limitations (Bäßler, 2018). Lattice structures are interconnected solid beam networks that are solid wall networks with included voids (D. Rosen et al., 2006a). The advantages of lattice structures are they can provide the same structural performance compared to the solid body with the same boundary conditions and volume (D. Rosen et al., 2006b).

2.3 Existing studies on DfAM implementation, approaches and tools used

There is a considerable amount of literature on DfAM, which focuses on tools, methodologies, and guidelines concerning DfAM. Although, some of the studies are not focused on providing information about which stage of the design process has more significance for the implementation of the DfAM. This study aims to consolidate the key points from different studies and tabulate their approaches for DfAM. As proposed by (Kumke et al., 2016a), in this study the existing literature is tabulated based on the approach, tools used, and at what stage the DfAM principles were adopted.

The articles chosen for study were mainly related to additive manufacturing and ones that emphasized on DfAM. Table 1 provides the data from the study of different literature on AM from different authors and their approaches. Interestingly, the majority of authors emphasized the combined use of methodologies which includes implementing both design and manufacturing rules of AM. However, this depended upon the phase of implementation too, for instance, the majority of the conceptual design implementation preferred AM Design. The combined approach of methodologies was prominently used when the authors choose all the design phases (Boyard et al., 2014a; Klahn et al., 2015; Ponche et al., 2014a; Rodrigue & Rivette, 2010a; D. W. Rosen, 2007; Vayre et al., 2012; S. Yang & Zhao, 2015). Therefore, in the case of this study where the design is in the conceptualization stage, the suitable approach is adopting design rules for AM. In the case of studies by (Adam & Zimmer, 2014; Gerber & Barnard, 2008; Kamps et al., 2017a; Laverne et al., 2015), AM design rules were given consideration and were implemented at the conceptual design stage.

Table 1 Study on approaches of DfAM in literature

Authors	Approaches and Methodologies (AM design principles or AM Manufacturing principles)	Design Phase chose for implementation of AM	Tools and Techniques used for problem solving and idea generation
(Adam & Zimmer, 2014)	**AM Design Rules**	**Embodiment design Detailed Design**	**Design rules Catalogues**
(Boyard et al., 2014b)	**Combined approaches and methodologies**	**Conceptual Design, Detailed Design**	**3D graph of functions**
(Doubrovski et al., 2012)	**AM Design Rules**	**Conceptual Design**	**Questionnaire**
(Gerber & Barnard, 2008)	**AM Design Rules**	**Embodiment design Detailed Design**	**No tools mentioned**
(Hague et al., 2004)	**AM Manufacturing principles**	**Conceptual Design, Embodiment design**	**No tools mentioned**
(Kamps et al., 2017b)	**AM Design Rules**	**Conceptual Design**	**TRIZ, Bio-mimicry database**
(Klahn et al., 2015)	**Combined approaches and methodologies**	**All Phases**	**Focus group-based data collection**
(Kranz et al., 2015)	**AM Design Rules**	**Embodiment design Detailed Design**	**Design rules Catalogues**
(Kumke et al., 2016a)	**Combined approaches and methodologies**	**All Phases**	**Design feature database**
(Laverne et al., 2015)	**AM Design Rules**	**Conceptual Design**	**Brainstorming**
(Maidin et al., 2012)	**AM Design Rules**	**Conceptual Design**	**Design feature database**
(Ponche et al., 2014b)	**Combined approaches and methodologies**	**Embodiment design Detailed Design**	**Design of Experiments**
(Rias et al., 2016)	**AM Design Rules**	**Conceptual Design**	**No tools mentioned**

Authors	**Approaches and Methodologies (AM design principles or AM Manufacturing principles)**	**Design Phase chose for implementation of AM**	**Tools and Techniques used for problem solving and idea generation**
(Rodrigue & Rivette, 2010b)	**Combined approaches and methodologies**	**Embodiment design**	**TRIZ**
(S. Yang & Zhao, 2015)	**Combined approaches and methodologies**	**Conceptual Design, Embodiment design**	**No tools mentioned**
(D. W. Rosen, 2007)	**Combined approaches and methodologies**	**Embodiment design Detailed Design**	**No tools mentioned**
(Salonitis & Zarban, 2015)	**AM Design Rules**	**Detailed Design**	**AHP, Multicriteria selection**
(Salonitis, 2016)	**AM Design Rules**	**Detailed Design**	**Axiomatic design**
(Seepersad et al., 2012)	**AM Design Rules**	**Embodiment design Detailed Design**	**No tools mentioned**
(D. Thomas, 2009)	**AM Design Rules**	**Embodiment design Detailed Design**	**Questionnaires, Survey, design of Experiments**
(Vayre et al., 2012)	**Combined approaches and methodologies**	**All Phases**	**Parametric Optimization**

2.4 Computer-Aided Design (CAD)

An article published by (Wilkes, 1990), describes the Computer-Aided Design (CAD) as a software system that enables designing components by the visual representation of components from various angles, references, and dimensions. CAD has developed as an integral part of the mechanical design process since the introduction of Sketchpad – one of the earliest CAD software in the 1960s (Sutherland, 1964). Computer-aided design (CAD) is defined as the use of computer systems to assist in the creation, modification, and analysis of a design (Groover & Zimmers, 1983). In practice designing in CAD software has no restrictions, although manufacturing restriction has always been a limitation. The exchange of data from CAD software to other applications such as AM software, CAE software is done using CAD formats. Commonly used neutral CAD formats are as follows (Xu, 2009),

- DXF (Drawing eXchange Format) (DXF, 2007)
- IGES (Initial Graphic Exchange Standard) (IGES, 2007)
- STEP (Standard for the Exchange of Product model data) (ISO 10303-1, 1994)
- 3DXML (3D Extensible Markup Language) (3DXML, 2007)

The CAD data may contain data from solid modeling, free-from surface/sheet modeling, or generalized cellular modeling with functions such as Boolean operations, thickening, fillet, or chamfering etcetera (Xu, 2009). Neutral formats are preferred while exchanging data between CAD to CAD or CAD to CAE software. However, there are several problems in transferring the model using these neutral formats (Dimitrov & Valchkova, 2011). According to (Xu, 2009), STEP format is a widely used neutral CAD format in the industries. The most common CAD data exchange format for AM are as follows (Chua et al., 2017a; Hällgren et al., 2016),

- STL (stereolithography).
- IGES (initial graphics exchange specification).
- STEP (standardized graphic exchange format).
- OBJ (object file).
- VRML (virtual reality modeling language).

CAD file formats such as STEP and IGES can be converted to STL (and other AM formats), and during this process, there is a possibility of some quality issues. These quality problems/defects can be topological errors, zero volume parts, or missing parts. Hence, the STL files may cause problems in downstream activities like Finite Element Analysis or NC tool-path generation (Xu, 2009). The modeling approaches used to create the design in CAD systems can be of Parametric modeling, non-parametric modeling, Implicit modeling, etcetera. Each modeling approach has its advantages and disadvantages. The following paragraphs discuss these approaches from different studies.

2.4.1 Parametric, Non-Parametric, and Implicit modeling:

According to (Chang, 2014), "The CAD product model is parameterized by defining dimensions that govern the geometry of parts through geometric features and by establishing relations between dimensions within and across parts". Therefore, a parametric model allows changing the shapes based on the relations defined while creating the model (Xu, 2009). The Parametric model generally contains information like dimensions, relationships, and constraints between geometries like edges, vertices, or sketches (Camba et al., 2016). This approach of modeling is very useful when developing the CAD models for future modifications based on parameters applied. Most professional CAD software uses a Parametric modeling approach for creating engineering models and drawings (Chua et al., 2017b).

According to (Magnacad LLC, 2017), the non-parametric modeling methodologies do not require a parent-child constraint relationship, rather models are created by Boolean operations of a set of analytic primitives to obtain the desired form. Unlike Parametric modeling, the non-parametric modeling of the geometric features is not governed by relationships or dimensions (Ma, 2005). These models are generally modeled like sculpturing and are usually dependent upon the designer's mind and approach. The modeling tools use a combination of primitive shapes and surface tools or polynurbs to generate shapes (Ranta et al., 1993).

Implicit modeling is where the modeling is done by generating surfaces using equations and distance functions (Payne & Toga, 1992). Unlike parametric modeling software which allows exporting Boundary representation (B-Rep) models, implicit modeling software only allows visual representation file formats generally STL formats or voxel data formats. With AM becoming more affordable and easier to use, complex models like Schwarz minimal models/Gyroids (Yoo, 2014) which are generated using implicit modeling can be designed and manufactured.

Considering the problem statement of this thesis, the models designed will be analyzed for its heat transfer performance and therefore the importance of parameters is very essential to compare and validate the suitable design for the application. Furthermore, to perform faster simulation and for better performance of the computational software, the Boundary representation (B-rep) version of the model is much suitable (Hamri et al., 2010). This is partly because the visual representation files are generally a representation of the surfaces using triangles, more the triangular faces, better are the representations (Dong et al., 2015). Therefore, it is hard to set up boundary conditions on these triangular faces.

2.4.2 Lattice Structures

Additive manufacturing allows tool-less manufacturing of complex geometries and this is limited to self-supporting structures. Even though complex geometric freedom is desired, in practice they are not possible in terms of complex overhanging geometries (Hussein et al., 2013). Hence, understanding the lattice structures and their geometries are important. This section of the literature review will be discussing the lattice structures and the theory behind it. Lattice structures are generally of three types, namely strut-based lattice, triply periodic minimal surfaces, and shell lattice structure (Maconachie et al., 2019a). According to (Nagesha et al., 2020), the lattice structures are found to have characteristics of lower relative density, lightweight, better strength, and elasticity compared to other solid structures.

<u>Strut-Based Lattice structures.</u>

Strut-based lattice structures are a series of struts/beams and nodes inside a defined volume (Syam et al., 2018a). Figure 7 illustrates a typical unit cell of a strut-based lattice structure with nodes (n) and struts/beams (p). A node is a joint where two or more struts meet, and the strut is the member that links or connects two nodes. There can be a number of feasible structures possible inside a unit cell if the nodes and struts are not constrained (Syam et al., 2018b). In this study only constrained lattice structures will be adopted for studies.

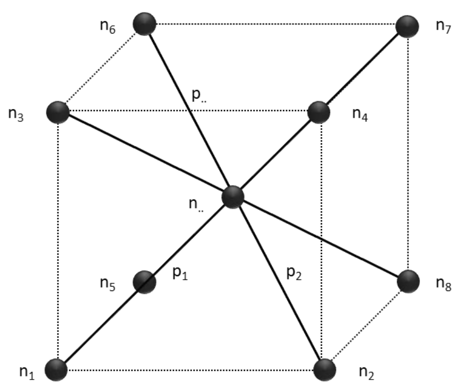


Figure 7 illustration of structure with nodes n and struts p

Triply periodic minimal surfaces (TPMS)

Triply periodic minimal surfaces (TPMS) are the lattice structures that contain unit cells made of minimal surfaces like Schwartz diamond, Neovius, Schwartz P, Schoen gyroid, etcetera. These structures contain topologies generated by implicit methods using mathematical formulae

$$f(x, y, z) = 0, \text{where } f = \mathfrak{R}^3\mathfrak{R}$$

as well as U = 0 defines the iso surface boundary between the solid and void sections (Maconachie et al., 2019b; Strano et al., 2013b). These surface structures are preferred for biological applications as porous scaffolded geometry is desired (Yoo, 2014).

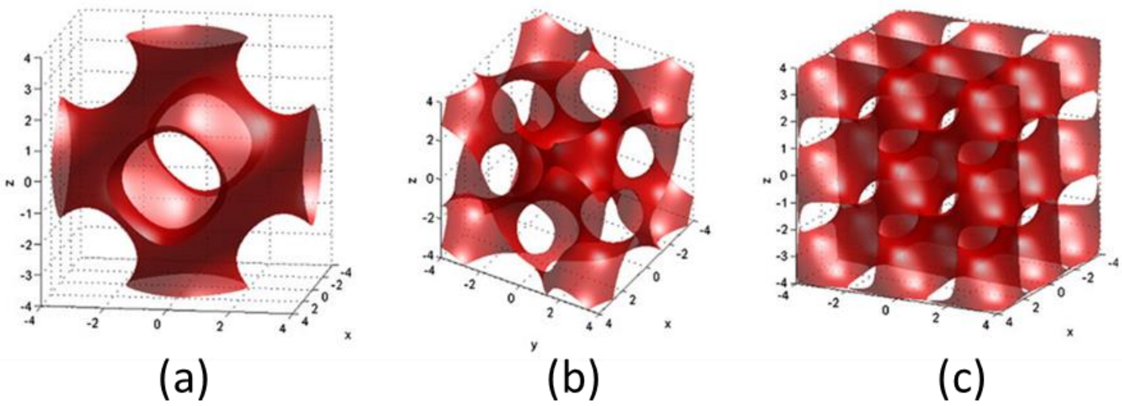


Figure 8 Representation of minimal surface equations (from left) (a) Schwartz (b) Gyroid (c) Diamond (Strano et al., 2013a)

The mathematical equation for the surfaces shown in Figure 8 are as follows (Klein, 1921),

a. Schwartz level surface equation,

$$\cos(x) + \cos(y) + \cos(z) = 0$$

b. Gyroid level surface equation,

$$\cos(x)\sin(y) + \cos(y)\sin(z) + \cos(z)\sin(x) = 0$$

c. Diamond level surface equation,

$$\sin(x)\sin(y)\sin(z) + \sin(x)\cos(y)\cos(z) + \cos(x)\sin(y)\cos(z) + \cos(x)\cos(y)\sin(z) = 0$$

There are several studies conducted on the application of TPMS structures to understand its capabilities in engineering applications. One study conducted by (N. Thomas et al., 2018) on thermal capabilities of TMPS structures, concluded that TPMS based structure has enhanced flux performance when compared to conventional net-type spacers.

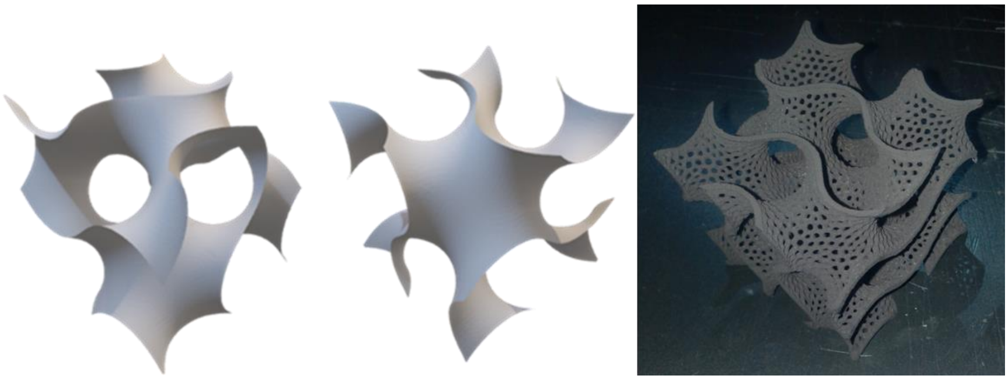


Figure 9 Schoen Gyroid representation and its printed version source:(Pixelrust, 2012)

<u>Shell Lattice Structure</u>

According to (Maconachie et al., 2019b), the shell lattice structure is described as “TPMS-like (though their surfaces do not necessarily have zero mean curvature) and are referred to as “shell lattices”. The shell type lattice structures are necessarily closed-cell type lattice structures made of plates. Due to problems associated with post-processing after printing (Bonatti & Mohr, 2019), open-celled shell lattice structures are now designed (Han et al., 2015). These structures exhibit superior stiffness and strength at low density when manufactured and tested for mechanical capabilities (Han et al., 2015).

2.5 Computer-Aided Engineering

Computer-Aided Engineering (CAE) is the use of computer software to simulate the performance of designs and models under specified boundary conditions to improve product design (Bahman & Iannuzzo, 2018). To achieve the design goals, the design is required to undergo analysis using CAE i.e., computer simulation. The goal of the design is to achieve optimal heat management. According to (Nowak & Wróblewski, 2011), the performance of a cooling system is the ratio of the mass-flow of the cooling air and the air inlet at the compressor. As mentioned in the problem statement the designed model will be air-cooled, therefore the heat transfer takes place first from the body and then the cooling surfaces and then from the cooling surfaces to the cooling fluid. The heat transfer that takes place through a combination of heat transfer between the solids and the heat transfer between the fluids is called Conjugate Heat transfer (Nicolas Huc, 2014). Figure 10 shows the difference between conjugate heat transfer and convective heat transfer. The governing equations considered for conjugate heat transfer problems are, For the unsteady and steady-state in fluid flows (John et al., 2019a):

- Law of conservation of mass (The continuity equation)
- Law of conservation of momentum (The Navier– Stokes equations, 2D or 3D depending on the nature of flow)
- Law of conservation of energy (The complete energy equation corresponding to the dimensionality of the flow)

For Unsteady and Steady conduction in the solid domain (John et al., 2019b):

- Two dimensional or three-dimensional unsteady energy equation
- Two- or three-dimensional steady Laplace or Poisson equations
- One dimensional steady or unsteady conduction equation upon considering prevented or negligible heat conduction in other dimensions as in case of heat conduction through thin plates

The case study in this research uses the help of computer simulations technique to solve the CHT. The software used to conduct Heat simulation is by Ansys AIM. The Ansys Fluent solves the energy equation in the form (Ansys, 2006),

$$\frac{\partial(\rho E)}{\partial t} + \nabla.\left[\vec{V}(\rho E + p)\right] = \nabla \cdot \left[k_{eff}\nabla T - \sum_j h_j J_j + \left(\bar{\bar{\tau}}_{eff} \cdot \vec{V}\right) + S_h\right]$$

Where,

$k_{eff}\nabla T$ = Conduction,

$\sum_j h_j J_j$ = Species Diffusion,

$\left(\bar{\bar{\tau}}_{eff} \cdot \vec{V}\right)$ = Viscous Dissipation

CHT for Aerospace components becomes complicated due to the interlinking of heat and structural loads in the simulation (John et al., 2019b). However, there is a considerable amount of research conducted in the application of CHT transfer simulation in studying the Aerospace engineering structures (Crowell et al., 2014; Dechaumphai et al., 1989; Huang et al., 2000). In their study (Zhao et al., 2011), proposed the coupling technique for the interaction between the flow and heat transfer. This technique is used in the three-dimensional governing equations for studying aerothermal-structural studies (John et al., 2019b).

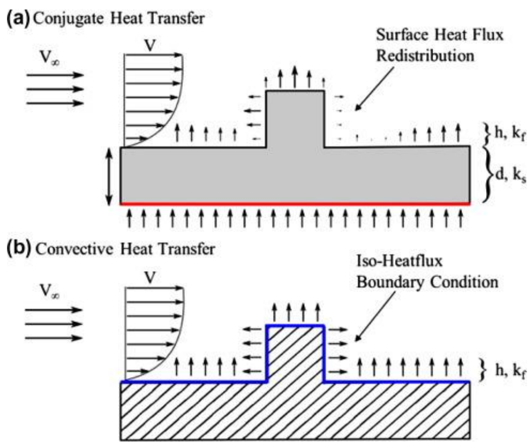
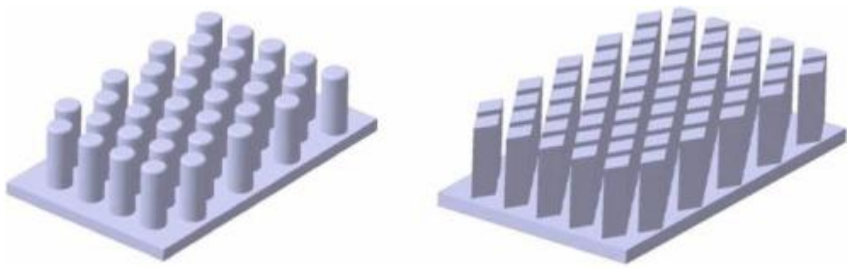


Figure 10 Conjugate and Convective Heat transfer (Li et al., 2016)

Extended Surface Heat transfer – Fin & Pin fins

To maximize the heat transfer using extended surfaces would be a viable option in the case of this thesis. According to (Shah, 2008a) "Extended surfaces have fins attached to the primary surface on one side of a two-fluid or a multifluid heat exchanger. Fins can be of a variety of geometry—plain, wavy, or interrupted—and can be attached to the inside, outside or both sides of circular, flat or oval tubes, or parting sheets." In addition to this, (Shah, 2008b) describes that Pin fins are used to increase the surface area enabling more heat transfer. Adding additional features or enhancing the geometries can also increase the heat transfer coefficient when compared to that of a plain fin. Furthermore, studies by (Furukawa & Yamauchi, 2018b) indicate that Fins are a very effective method for heat transfer with better reliability. The authors (Furukawa & Yamauchi, 2018a), also suggest that there are two ways to increase the heat transfer: one by increasing the surface area near the solid-fluid region and the other by increasing the amount of heat transfer per unit area.



(A) (B)

Figure 11 (A) Circular Pin and (B) Diamond Pin (Furukawa & Yamauchi, 2018a)

Pins fins seem to be ideal for the application in the case study of this thesis, although this requires a detailed comparison of the advantages and disadvantages between the other similar structures like lattice structures or Gyroids. However, Pin Fins would have more preferences to other structures (Shah, 2008b).

2.6 Lean Six Sigma

The journey of modern Six-Sigma methodology begins with Motorola from 1987, following the success of General Electric and Allied Signal deployed to improve their financial performance (Mader, 2008). The concept of lean was introduced first by Toyota under their Toyota Production System, however, it is believed that they learned the concept from Ford's manufacturing system (Dekier, 2012). With over 3 decades of experimentation of implementing Lean Six-Sigma (LSS) by different companies in various domains inside the companies, the LSS has evolved to become a "large collection of tools that the organization can bring to bear as appropriate on identified issues to achieve continual improvement across the entire organization" (Munro, 2015). Adaptation of the LSS tools in the continual improvement process depends upon the purpose and objective of the LSS program. The core idea of Six-Sigma is to make use of the data from different parameters within the identified department and use statistical tools to analyze and make decisions in the improvement process. Therefore, the Six-Sigma can be called a data-driven decision making process rather than opinion (or intuition) based decision making process.

Lean Six-Sigma (LSS) is a combined form of methodologies of both Lean and Six-Sigma, it is important to understand the difference between these to understand the approach used in this thesis. Lean emphasizes more on speed and waste, whereas Six sigma emphasizes more on variation, defects, and process evaluation (Antony, 2011). Table 2 shows the main differences that can be found between the two methodologies. The problems vary from company to company; therefore, the best way to approach problem-solving is to use the right tools and methods of both Lean and Six-Sigma. This thesis aims at using the right tool at the right stage of problem-solving to make the design workflow to be better, efficient and faster for the engineers in the design process.

Table 2 Difference between Lean and Six Sigma methodologies

Methods	Lean	Six Sigma
The importance is given to	Waste, Speed	Eliminating sources of Variation, Defects, Process Evaluation
The approach of problem-solving	Plan, Do, Check, Act	Define, Measure, Analyze, Improve, Control
Process events	Kaizen Rapid Improvement	Projects with stage gate

2.6.1 **Design for Six-Sigma (DFSS)**

To achieve a well-established LSS system, the companies have to invest a significant amount of effort, resources, and money during the initial stage of implementation of LSS. Therefore, the small scale enterprises (SMEs) and start-ups get discouraged to try and implement LSS due to the additional burden of cost and amount of resources and time (Jayathirtha, 2013) despite knowing the potential of LSS. Start-ups and SMEs heavily rely upon innovation to keep up the competition with the existing players and large-scale companies in the market. The better the quality and reliability of the product, the better is the success rate of the start-ups and SMEs (Cooper & Kleinschmidt, 2007). Therefore, to improve the quality of the product, the manufacturing department must strive hard to achieve the best quality with minimum costs and rejections. The general approach to achieve this is the use of LSS to improve the quality of the manufacturing process (Kumar Sharma & Gopal Sharma, 2014). In contrast, implementing LSS in the design stage improves the quality (Ida & Jean-Baptiste, 2012) and lowers the rejections in the manufacturing process, which otherwise, were caused due to poor design considerations during the design stage. Thus, the design for Six-Sigma comes into the picture.

According to (K. Yang & El-Haik, 2008), "Design for Six-Sigma (DFSS) is the Six Sigma Strategy working on early stages of the process life cycle. It is not a strategy to improve the current process with no fundamental changes in process structure". The DFSS implementation starts at an early stage of the life cycle of the process with goals and objectives to improve in the final product (Brue & Launsby, 2003). The DFSS implements all the best available tools and methods known today to optimize and improve the design of the product to reach the best version of the product, by reducing the redundancies and uncertainties during the design process (Munro, 2015). Introducing lean concepts into DFSS will eliminate wastes in the design process. For example, when designing a machine element with high strength to weight ratio, performing topology optimization with all the loading and manufacturing constraints before performing a load-bearing test will reduce the number of iterations in the design process.

2.6.2 **Design for Six-Sigma and Design for Additive Manufacturing (DfAM).**

Additive Manufacturing (AM) has removed the majority of the design constraints which were previously not possible to manufacture using traditional manufacturing methods like Subtractive or Formative Manufacturing (Diegel et al., 2019). Hence, the design process/workflow for the AM becomes different from the design for the traditional manufacturing process. For instance, the light-weighting of the body in the design for traditional manufacturing methods was by introducing through holes, collars in the edges, and so on (Kamal & Rizza, 2019). On the other hand, the design for AM allows using shell objects with infill of lattice structures or gyroid structures. Therefore, bringing down the overall weight to a significant level compared to the same object designed for traditional manufacturing, without reducing the structural integrity (Kamal & Rizza, 2019). The DfAM involves numerous parameters concerning the design principles of AM and the design requirement itself. The applications such as heat transfer, fluid flow require design elements that are created specifically for the application considering their behaviors at different regions of the design element (Furukawa & Yamauchi, 2018a). These structures, typically the lattices which are not self-supporting may cause deformity or support structures during the printing process (Langelaar, 2016). In order to improve this, the designer must consider a variable that denotes this problem. Henceforth, there will be several different variables just for structural design. Likewise, considering the Multiphysics analysis of the structure, each type of structure will exhibit particular results and the result objectives will be considered as variables that are affected by the variables of the structural design (John et al., 2019b). Figure 12 shows the heatsink developed with manual design manipulation and computer-based topology optimized design:

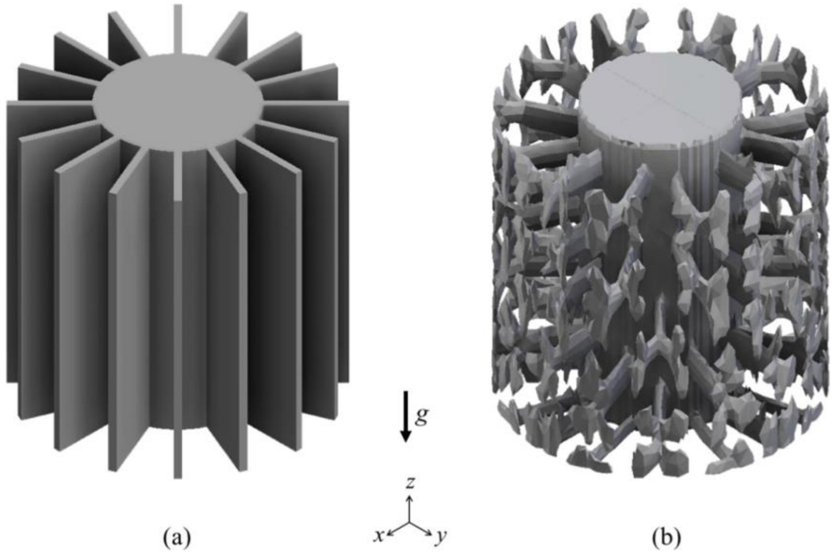


Figure 12 (a) Radial plate-fin heat sink (b) 3-D topology - optimized heat sink (Joo et al., 2018)

Hence, a relationship between these variables can be developed and visual tools like graphs and pie charts can be used to represent them. Therefore, to reduce the redundancies in the calculations/analysis as shown in Figure 13 and improve efficiency the Design for Six Sigma (DFSS) is introduced.

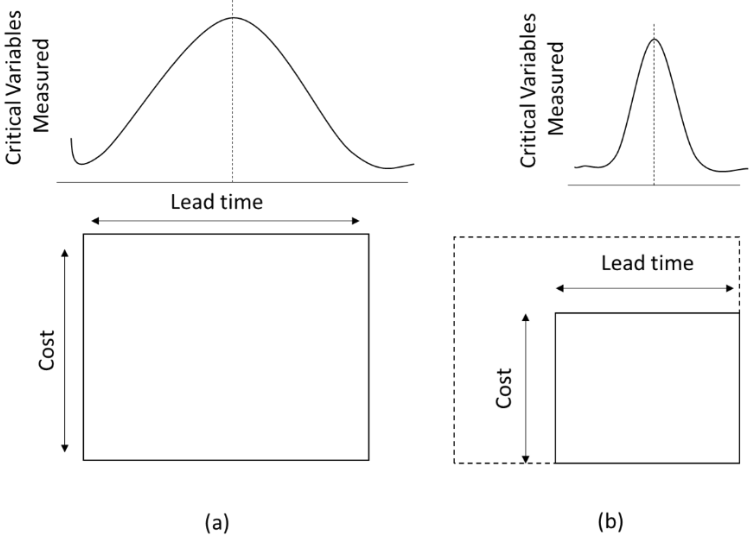


Figure 13 Design Process (a) Without DFSS (b) With DFSS

A study by (Pradel et al., 2018b) concluded that the designers still see AM as a very good rapid-prototyping tool. This is because of their limited build volume and the barriers such as high cost which prevents it from used for mass production. Therefore, designers do not see AM as the manufacturing method like they see the conventional manufacturing methods. Hence, the need for learning AM specific designs rules are less understood by them. In addition to this, a study by (Bikas et al., 2019), summed up as "the existing design for manufacturing rules (DFM) for conventional processes contribute to the designer's psychological inertia, which drives the part design away from the AM advantageous nature." Therefore, before proceeding through the DFSS methodology the designer must be well aware of the design principles of Additive Manufacturing (AM).

2.6.3 **Design for Six-Sigma (DFSS) Phase:**

The design for Six-Sigma can be achieved by using any one of the many established methodologies such as DMADV (Design-Measure-Analyze-Design-Validate), IDDOV (Identify-Define-Design- Optimize- Validate), IDOV (Identify-Design-Optimize-Validate), DMADOV (Design-Measure-Analyze-Design-Optimize-Verify) (Asad et al., 2006).

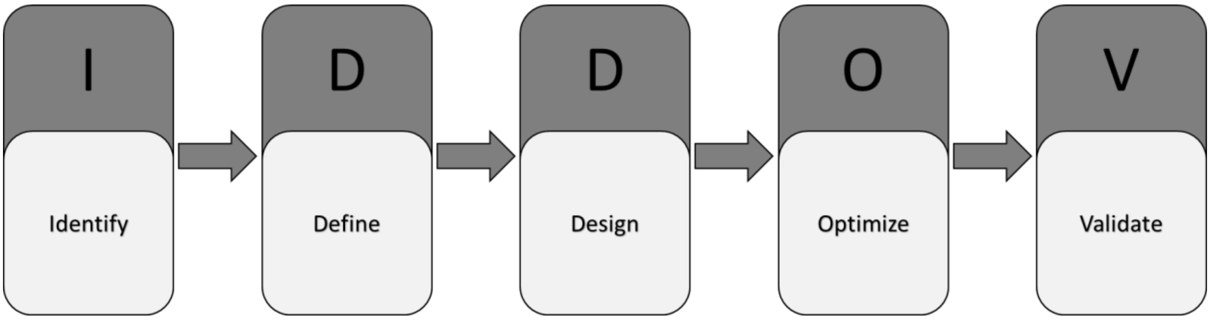


Figure 14 Design for Six-Sigma (DFSS) - IDDOV Phases

This thesis has taken the IDDOV methodology adopted by the book *Design for Six Sigma in Product and Service Developmen*t by (Cudney & Furterer, 2016). Figure 14 shows the IDDOV methodology flow of operational stages, all the operational stages are interconnected. The IDDOV process is generally used for developing a new product or process which did not exist before or needs to be developed from scratch. According to (Cudney

& Furterer, 2016), "The benefits of applying Design for Six Sigma and IDDOV compared to Six Sigma and DMAIC are that you are not constrained by an existing process, and you do not need to collect large amounts of the voice of process (VOP) data, or spend time baselining a non-existent or seriously broken process."

IDDOV methodology roadmap will be further discussed based on the steps, tools, and techniques relevant to the thesis, i.e., the steps, tools, and techniques required for developing an engineering design for the specific application. As a project manager, one can choose the right tool and take its complete advantage depending upon its outcome, because there is no standard approach for DFSS (Mader, 2003). Therefore, out of all the tools available only selected tools and techniques shall be discussed in the following paragraphs. The activities listed in different phases of the IDDOV occur concurrently as shown in Table 3. The activities illustrated in each phase are briefly explained in the following paragraphs.

Table 3 DFSS IDDOV Activities for Process and Product Design (Cudney and Furterer 2016)

Identify	Define	Design	Optimize	Validate
1. Develop project charter	4. Collect the voice of the customer (VOC)	7. Identify process elements	10. Implement pilot process	13. Validate process
2. Perform stakeholder analysis	5. Identify critical to satisfaction (CTS) measures and targets	8. Design process	11. Assess process capabilities	14. Assess performance, failure modes, and risks
3. Develop Project Plan	6. Translate VOC into technical requirements	9. Identify potential risks and inefficiencies	12. Optimize design	15. Iterate design and finalize

2.6.3.1 Identify Phase

The goal of the Identify phase is to identify the design challenge in the project, scope of the design project through the development of a project charter, and identify the entities or stakeholders that the project has impacted (Jenab et al., 2018). The emphasis in this phase is to define the requirements of the design project.

The major activities in this phase are as follows (Cudney & Furterer, 2016):

1. Develop project charter
2. Perform stakeholder analysis
3. Develop Project Plan

The Projector charter is usually a formal short document consisting of a description of the project including the objectives, procedures, or methods used to execute and the stakeholders involved. In the stakeholder analysis, the impact of the project on the customers and stakeholders are evaluated (Munro, 2015). The quality of the design project is set by understanding the requirements and expectations set by the consumers. The customers need not be external always, the customers can be the internal stakeholders too. In the case of this thesis, the customer is internal. Once the required information is gathered, the project plan is developed (Cudney & Furterer, 2016). It includes the developing detailed work plan, work breakdown structure (WBS), and the plan with information on roles, responsibilities, estimated duration of the activities. Table 4 shows the tools and techniques that can be used in the identify phase.

Table 4 DFSS - Identify Phase tools and Techniques (Cudney & Furterer, 2016)

Identify Activities	Tools, Techniques
Develop Project Charter	Project Charter Risk Matrix
Perform stakeholder analysis	Stakeholder analysis definition Stakeholder commitment scale Communication Plan
Develop a project plan	Project plan Responsibilities matrix Items for resolution (IFR) Ground rules

2.6.3.2 Define Phase

The defined phase aims at understanding the Voice of Customer (VOC) and then the customer's requirements are defined in the Critical to Satisfaction (CTS) characteristic to interpret them into the technical specifications of the product or process to be designed (Cudney & Furterer, 2016).

The following are the activities involved in the define phase according to the methodology followed by (Cudney & Furterer, 2016),

1. Collect the voice of the customer (VOC)
2. Identify CTS measures and targets
3. Translate VOC into technical requirements

The VOC is vital in the process of product development, which enables the designers to reach the minds of the user or customer requirement and develop the technical elements in the final product (Jenab et al., 2018). Figure 15 demonstrates the common knowledge gap and misunderstanding between engineers and customers.

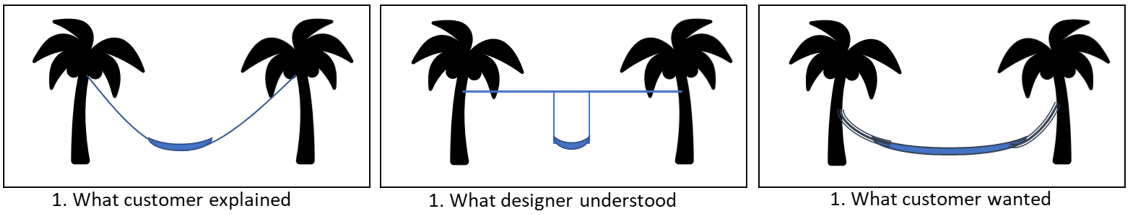


Figure 15 Customer expectations Vs Designer understandings

To avoid the uncertainties and understand the design constraints it is important to understand the customer requirements/user requirements. In the case of this thesis, the major requirement is the application of the design by the next stakeholder.
After establishing a sound VOC, the next step is to develop metrics for CTS where the VOC is classified into the measures and targets. The criteria for CTS are defined to satisfy the requirements established in the VOC. Table 5 shows the tools and deliverables that can be used during this stage. The next step is to translate VOC into technical

requirements for developing the design. The best tools for this purpose are Quality Function Deployment (QFD) and the House of Quality (HOQ). “A set of planning and communication routines, quality function deployment focuses and coordinates skills within an organization, first to design, then to manufacture and market goods that customers want to purchase and will continue to purchase.” (Hauser & Clausings, 1996). The define phase activities and the tools & techniques involved are shown in the table below,

Table 5 DFSS - Define Phase activities and Tools/Techniques used (Cudney & Furterer, 2016)

Define Activities	Tools, Techniques
Collect the voice of the customer (VOC)	Data collection plan VOC Interviewing, surveying, focus groups Market research
Identify critical to satisfaction (CTS) measures and targets	Critical to satisfaction (CTS) summary and targets Affinity diagram Quality function deployment (QFD) Operational definitions Strength-weakness-opportunity-threat (SWOT) analysis
Translate VOC into technical requirements	QFD Benchmarking Kano analysis

2.6.3.3 Design Phase

The objective of the Design phase is to (Brue & Launsby, 2003) “build a thorough base of knowledge about the product or service and its processes.” The design engineers aim to translate the customer requirements into (Brue & Launsby, 2003) “functional requirements and alternative concepts or solutions; through a selection process, the team evaluates the alternatives and reduces the list of solutions to one, the best-fit concept.” The main activities in the design phase are as follows (Cudney & Furterer, 2016),

1. Identify process elements.
2. Design process.
3. Identify potential risks and inefficiencies.

Considering the context of this thesis, which aims at developing a design solution, the activity ‘Identify process elements’ is nothing but identifying the design elements specified by the customers during the activity VOC. The process of generating the design elements may use the statistical approach or by traditional techniques such as brainstorming and the Nominal Group Technique (Brue & Launsby, 2003). The next activity is the design process, which is the most important activity considering all the DFSS phase activities. According to (Brue & Launsby, 2003), “For each technical requirement, the team identifies critical-to-quality design parameters (CTQs) and their influence on the technical requirements (transfer functions), using analysis, Design of Experiments (DOE), simulation, and/or modeling— representations of the relationships (Y = f(X)) between customer requirements (Y’s) and design elements (X’s).”

Table 6 Pugh's Concept Selection Technique. (Cudney & Furterer, 2016)

	Concepts						
Criteria	1	2	3	4	5	6	7
A	–	–	–	0	Candidate	0	–
B	–	0	–	–	Concept	0	–
C	+	+	–	–		–	–
D	+	–	–	+		–	+
E	+	+	–	–		–	–
Pluses	3	2	0	1		0	1
Minuses	2	2	5	3		3	4
Zeros	0	1	0	1		2	0

The concept designs generated through the design phase need to be narrowed down and the best designs are to be selected for the next stage. The Pugh Matrix(PM) is a technique which "allows comparison of a number of design candidates leading ultimately to which meets a set of criteria" (Burge & Churchill, 2009). The idea behind PM is to select one of the concepts as the "candidate concept" and then compare it with each of the other concepts for selected comparison criteria in a table with columns and rows. According to (Cudney & Furterer, 2016) during the comparison with PM, "If the new concept is better than the candidate for those criteria, you would place a plus sign (+) in the cell where the new concept intersects the criteria. If the new concept is worse than the candidate concept for the criteria, a minus sign (–) is placed in the cell. If the new concept is the same as the candidate on those criteria, a zero (0) or S for the same is placed in the cell". The concepts with few minuses and more pluses would be selected for the next step, as well as the weaknesses of the selected ones can be targeted for improvements. The Table 6 shows Pugh Matrix.

During the design process, there are instances of decision making for choosing the right attributes, requirements, and features out of the available options. Analytic Hierarchy Process (AHP) is one such powerful tool used for decision-making. AHP was first introduced by T.L Saaty (Zhang et al., 2009), which is a tool for decision-making when there are multi-structure complexes and multi-attributes are involved (Fong & Choi, 2000). AHP calculates the priorities of the individual choices based on the judgment of the decision-maker (Balubaid & Alamoudi, 2015). The designs undergo further refining by conducting computer simulations for better-optimized designs to reach the targeted goals. The data from different simulations are recorded for the next phase of optimization. In case of the application of DFSS for a final product, then the potential risks and inefficiencies of the design are identified. The activities involved in the design phase are shown in Table 7

Table 7 Design Phase Activities and Tools/Deliverables (Cudney & Furterer, 2016)

Define Activities	Tools, Techniques
Identify process elements	Process element summary
Design process	Basic statistics, Process analysis Simulation Prototyping Criteria-based matrix Pugh concept selection technique Voice of the process (VOP) matrix
Identify potential risks and inefficiencies	Failure mode and effect analysis (FMEA) Risk assessment Process analysis Waste analysis

2.6.3.4 Optimize and Validate Phase.

Considering the thesis, the optimize phase in the process of the design mainly focuses on improving performance and reliability. Although, in general, the purpose of the Optimize phase is to achieve a balance of quality, cost, and time to market (Brue & Launsby, 2003). Tools like the design of experiments can be used for identifying the factors that impact the quality of the design by statistically analyzing the results (Munro, 2015). The optimization can be further improved by using data analysis tools like Histogram, Pareto charts, Pie-charts (Cudney & Furterer, 2016). The idea behind the optimization phase is to make sure the designed solution matches the requirements specified during the defined phase. The general steps involved in the Optimize phase,

1. Implement pilot process
2. Assess process capabilities
3. Optimize design

In the validate phase, the designed solution is assessed for its performance, and compared to the requirement by the customer, if it does not meet the required objective then the design is revised (Brue & Launsby, 2003). Each new iteration the design goes through after validation, better the design solution. One of the tools commonly used in the validate phase is the Concept verification Scorecard as shown in Table 8. The idea behind this is, to check the status of all the deliverables accepted in the define phase and add remarks (Cudney & Furterer, 2016). If the deliverables are not met, then the design process enters the iteration loop.

Table 8 Concept verification Scorecard

Deliverables	Status	Remarks

3 Methodology

One of the goals of this research was to identify the best tool for the workflow in Design for Additive Manufacturing. This required a detailed study of CAD workflow on creating complex shapes that can reap the advantages of the AM. The integration of computers into engineering design to create and modify is commonly known as Computer-aided design (Bilalis, 2000). There are several approaches to create the designs, to fulfill the requirement in this study we shall consider three approaches namely Parametric, Non-Parametric, and Implicit designs. In the parametric design approach, the geometries created are governed by parameters, references, and constraints. Whereas, in the non-parametric design approach the geometries are created based on the references of existing points and by using primitive shapes or polynurbs. And an implicit modeling approach creates the shapes using mathematical functions and equations.

3.1 Creating Parametric Lattice structures.

The lattice structures are generated using Siemens NX and the nTop platform. The custom rules are created in both the software lattice library. Figure 16 shows the unit cell for uniform and non-uniform thickness lattice structure. The pattern is automatically replicated by the software inside the model given as a reference area.

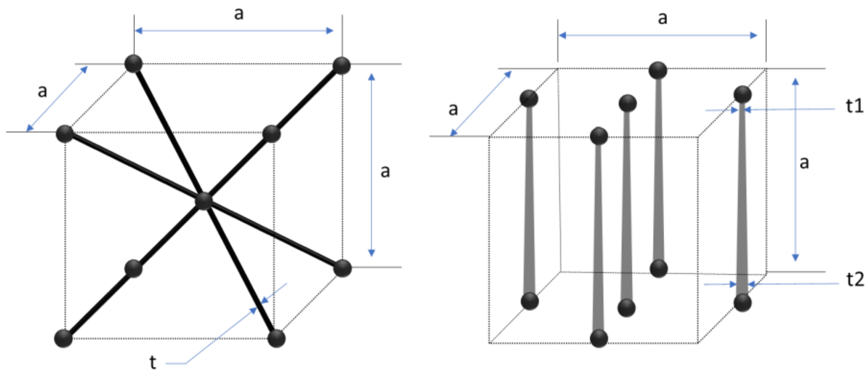


Figure 16 Unit cell with struts and node. (a) uniform thickness lattice (b) non-uniform thickness lattice

The number of unit cells in x, y, z direction is chosen based on the size of the lattice to be fit inside the reference geometry. For example, if the height of the reference geometry is 10 mm, the height of the unit cell will be 10 mm corresponding to the number of unit cells in the z-direction, which is 1. Similarly, if the number of unit cells in z is 2, then the height of the lattice structure would be 5 mm. This same methodology is followed for generating the gyroid structures using the nTop Platform. But with Siemens NX it is drawn manually using the surface modeling tools.

Figure 17 Lattice generation methods in Softwares (NX and nTop Platform)

Creating Gyroid structures using mathematical expressions in software,
Gyroid lattice structures can be generated using codes which contain equations for the implicit generation of the lattice structures like gyroids, The mathematical equation for the surfaces shown in Figure 18 are as follows (Klein, 1921),

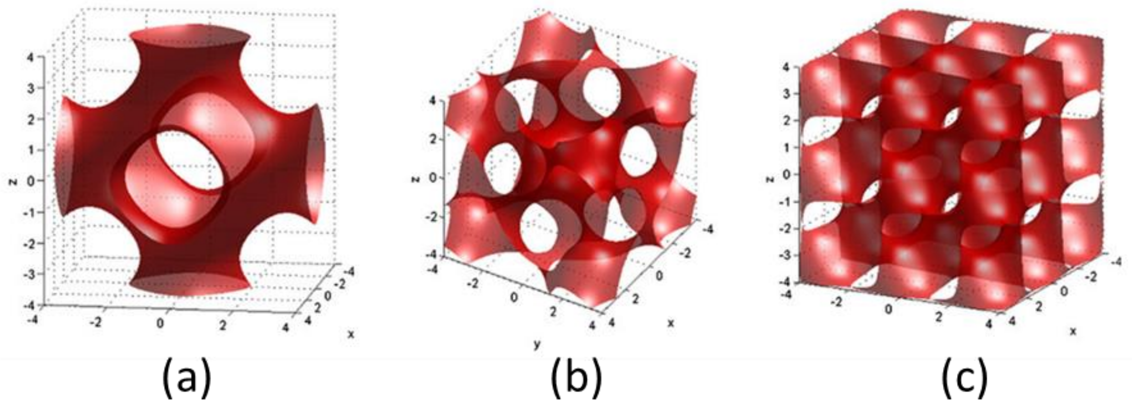


Figure 18 Representation of minimal surface equations (from left) (a) Schwartz (b) Gyroid (c) Diamond (Strano et al., 2013a)

a. Schwartz level surface equation,

$$\cos(x) + \cos(y) + \cos(z) = 0$$

b. Gyroid level surface equation,

$$\cos(x)\sin(y) + \cos(y)\sin(z) + \cos(z)\sin(x) = 0$$

c. Diamond level surface equation,

$$\sin(x)\sin(y)\sin(z) + \sin(x)\cos(y)\cos(z) + \cos(x)\sin(y)\cos(z) + \cos(x)\cos(y)\sin(z) = 0$$

3.2 Conjugate heat transfer

Conjugate heat transfer refers to the heat transfer between solids and the liquid region (Dorfman, 2010). To conduct the CHT simulation in this study, the Ansys AIM software is used. The Ansys solves the energy equation in the form (Sidebotham, 2015),

$$\frac{\partial(\rho \mathrm{E})}{\partial \mathrm{t}} + \nabla.\left[\vec{\mathrm{V}}(\rho \mathrm{E} + \mathrm{p})\right] = \nabla \cdot \left[k_{\mathrm{eff}}\nabla \mathrm{T} - \sum_{j} h_j J_j + \left(\bar{\bar{\tau}}_{\mathrm{eff}} \cdot \vec{\mathrm{V}}\right) + S_h\right]$$

Where,

$k_{\mathrm{eff}}\nabla \mathrm{T}$ = Conduction,

$\sum_j h_j J_j$ = Species Diffusion,

$\left(\bar{\bar{\tau}}_{\mathrm{eff}} \cdot \vec{\mathrm{V}}\right)$ = Viscous Dissipation

3.3 Software Tools Used

3.3.1 **Siemens NX**

The manual designs of minimal surfaces by the parametric design approach as well as the lattice generation based on input parameters used for the case study was done using Siemens NX. The version of the software used was 12.

3.3.2 **nTop Platform**

The lattice structures (both minimal surfaces and cellular/strut structures) used in the case study were generated based on input parameters using the nTop Platform.

3.3.3 **Ansys AIM**

The student version of Ansys AIM is the software that is being used for computational analysis in the study. The Fluid-Structure Heat Transfer module in the software allows the study of the heat transfer between the model and the coolant.

The steps involved in the software is as follows (Ansys, 2016),

- Step 1) Choose the Fluid-Structure Heat Transfer module.

- Step 2) Define the fluid flow physics region
- Step 3) Define the thermal physics region
- Step 4) Review the boundary condition
- Step 5) Review the region interface
- Step 6) Generate a solution
- Step 7) Analyze the results

3.3.4 **MATLAB**

The demonstration of using implicit modeling of minimal surfaces using mathematical function-based computer code was done using MATLAB.

3.3.5 **KDsurf**

KDsurf is a free software tool that allows generating minimal surface models using mathematical functions. It has an in-built library of over 20 different types of minimal surfaces.

3.3.6 **AHP Online Calculator**

AHP Online Calculator is a free web-based tool for conducting AHP calculation. This tool is used for choosing simulation software in the case study

3.4 Design for Six Sigma

Design for Six Sigma (DFSS) is a methodology that uses principles of Six-Sigma to design products and processes used to manufacture them. DFSS employs the methodology of IDOV (Identify, Design, Optimize, and Verify) during the development of a new product (Bauelas & Antony, 2004). In order to develop the workflow for the case study chosen in this study, the DFSS methodology IDDOV (Identify, Define, Design, Optimize and Verify) as described by the authors (Cudney & Furterer, 2016) is used. The reason for integrating DFSS in the study is to streamline the process of development by identifying all the necessary variables in the design process and integrating them in the right stages of the design process. The tools and techniques adopted in each stage of the design process are as tabulated in Table 9.

Table 9 DFSS tools used in different phases of the design process of the case study

Identify	Define	Design and Optimize	Verify
Project Summary	Voice of Customer	Concept Generation	Concept Verification Scorecard
Project Plan	Customer Requirement Form	Pugh Concept Selection	
Project Schedule	Customer Requirement Ranking		
	Analytic hierarchy process		

3.4.1 **Analytic hierarchy process (AHP)**

AHP technique is used for selecting the right software in the case study for conducting the Conjugate Heat Transfer simulation. The selection criteria for the software based on the requirement for the study are listed. Each criterion is given a rating based on the importance as shown in the 1-9 scale provided in Table 10. This is followed by the steps as shown in Figure 19 and then the calculation of consistency ratio. In this study, free software (Goepel, 2018b) available in the online version is used to perform the calculations.

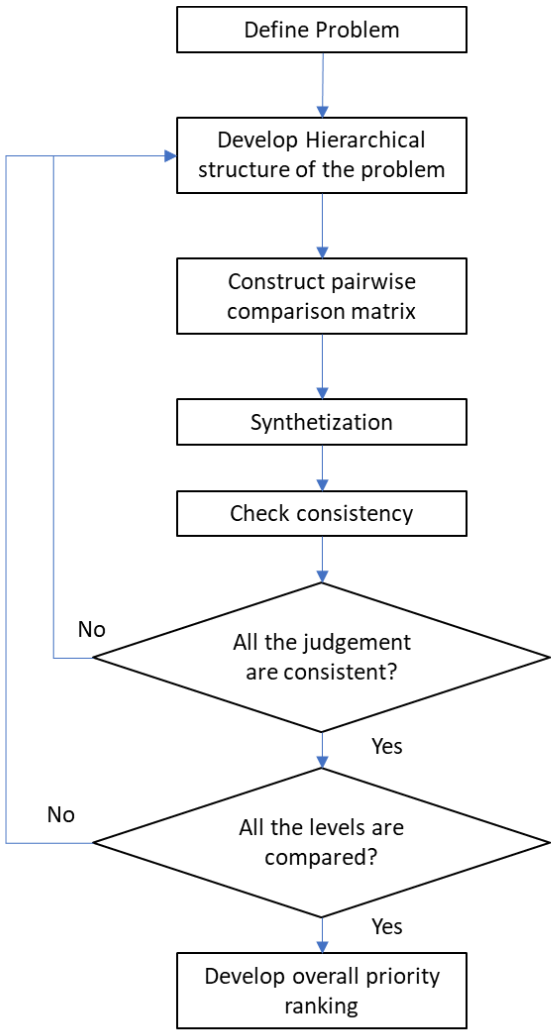


Figure 19 Analytic hierarchy process methodology (Kassem et al., 2017)

The formulae used in different stages of AHP are (Khwanruthai, 2012),

- Pairwise comparison

The importance of different criteria is tabulated to compare against each other. For example, if there is 3 comparison, then the matrix would of an order 3 x3

If a_{ij} is the element in row i and column j of the matrix, then the lower diagonal is filled with the formulae

$$a_{ji} = \frac{1}{a_{ij}}$$

- Consistency Analysis

The consistency index is calculated using,

$$Ci = \frac{\lambda \max - n}{n - 1}$$

The consistency ratio is calculated using,

$$CR = \frac{CI}{RI}$$

Where RI is a random index

Table 10 The 1-9 Scale in the AHP (Zhang et al., 2009)

Scale	Definition
1	Equal importance
2	Weak
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong or demonstrated importance
8	Very, Very strong
9	Extreme Importance

4 Results

This chapter discusses the results in two sections. In the sections (4.1, 4.2), the detailed workflow for designing each type of lattice and simulating them is presented. In addition to that, the information such as the time taken, software used, and their remarks for the completion of the tasks in the case study section (4.2) is illustrated. In the third section (4.3), the results from the implementation of DFSS in the design process are presented. In the fourth section (4.4), the conclusion from the design and simulation workflow is presented.

4.1 Lattice structure design workflow

This section of the thesis discusses the workflow for creating Lattice structures using CAD software. The software used and computer hardware is tabulated in Table 11. The time taken for generating/creating the surfaces are tabulated in Table 12. The components designed in this workflow are used as concepts in the case study. The results from this workflow will be analyzed to choose the right method of designing and the conclusion will be presented in section 4.4. Each section represents the workflow for the respective design software used.

Table 11 Hardware and software used for lattice design

Operating System	**Windows 10**
Processor	**Intel – i7 – 9th Generation**
RAM	**32 GB**
Graphics Card	**Nvidia GeForce RTX 2070**
Software used	**Siemens NX, nTop Platform, KDsurf, MATLAB**

4.1.1 Reports from lattice structure design workflow

Build volume: 50 mm x 50mm x 4 mm

Table 12 Report from the lattice structure design workflow

Structure Name	Method	Software	Time Taken	Remarks
Gyroid	Manual	Siemens NX	2 hours for designing and exporting	As structures get complicated, the computer is hard to operate. The thickness of the surfaces cannot go beyond .8 mm, as it creates a self-intersecting surface.
Schwarz P	Manual	Siemens NX	2 hours for designing and exporting	As structures get complicated, the compute is hard to operate.
Pin Fins (Lattice)	Manual	Siemens NX	1 hour for designing and exporting	As structures get complicated, the computer is hard to operate
Lattice Structures	Automated Generation using parameters	Siemens NX	30 minutes (Designing and Exporting)	As structures get complicated, the compute is hard to operate
Face type lattice	Automated Generation using parameters	nTop Platform	< 30 minutes (Designing and Exporting)	No performance issue
Cellular lattice	Automated Generation using parameters	nTop Platform	< 30 minutes (Designing and Exporting)	No performance issue
Gyroid TPMS	Automated Generation using parameters	nTop Platform	< 30 minutes (Designing and Exporting)	No performance issue

Siemens NX

Siemens NX (NX) is a powerful tool for CAD designers which provides strong surface modeling, solid modeling, and Boolean features. The workflow for creating lattice structures and minimal surface body is discussed in the following paragraphs. From version 11.0.2 onwards (Siemens NX, 2019), the lattice structures were introduced in NX.

<u>Creating Lattice structure:</u>

The workflow begins with the creation or importing a solid body (or surface body) and then using them as a reference to generate the type of lattice required. The template library of the NX has over 15 different types of lattice structures and it also allows to custom create the type of lattice the user needs in a cellular structure. The lattice once created cannot be modified, in case of any requirement to modify, the whole lattice must be deleted, and the new lattice is created from scratch. It must also be noted that the NX treats the structures generated as a facet body, it does not allow exporting them as Solid-body formats like .step or .iges. The following Figure 20 shows some of the built-in lattice structures (unit cells) available in NX.

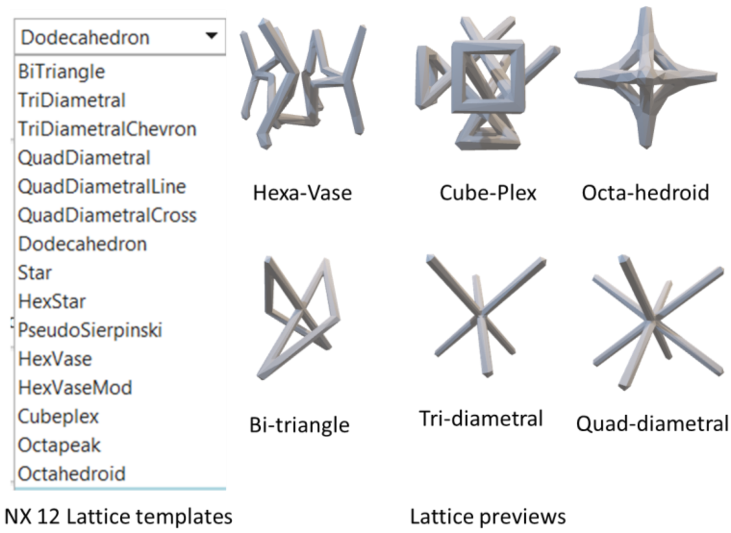
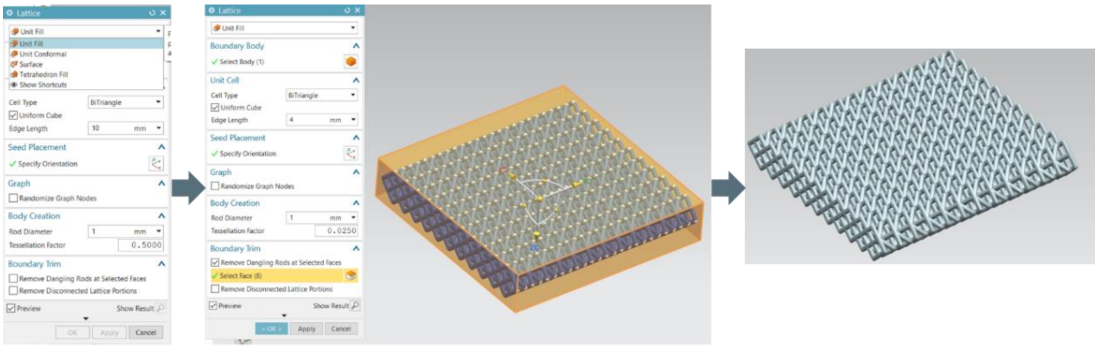


Figure 20 Built-in library of lattice structures in NX

The workflow for creating a unit fill type lattice,

- Step 1) Select a model as a reference for generating the lattice structure and select the infill option
- Step 2) Select the type of the lattice and fill the required parameters, then click OK

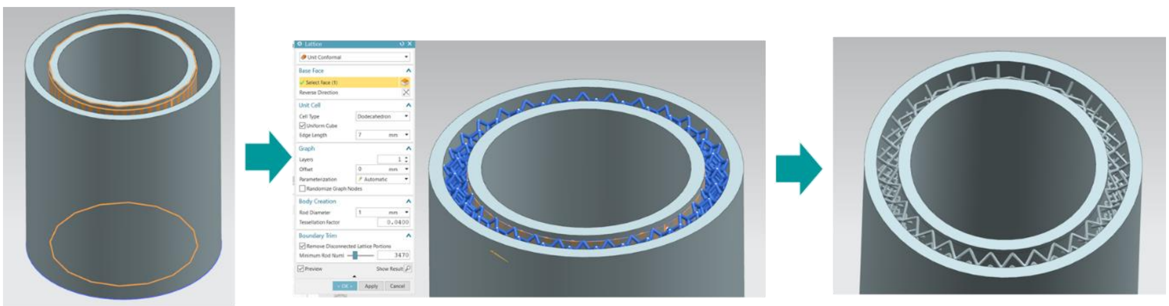


Step 1 Step 2 Lattice Preview

Figure 21 Workflow for creating a unit fill type lattice in NX

The workflow for creating Unit conformal type lattice,

- Step 1) Select a model surface as reference for generating the lattice structure and select the infill option
- Step 2) Select the type of the lattice and fill the required parameters, then click OK



Model for reference Step 1 Preview of Lattice after lattice generation

Figure 22 Workflow for creating Unit conformal type lattice in NX

Creating Minimal surface lattice structures:

Siemens NX (NX) does not have an inbuilt option to generate minimal surfaces, these surfaces are to be created using the surface modeling commands in the NX. The following discusses the steps involved in creating a minimal surface – Gyroid.

For non-conformal gyroid:

- Step 1) Create a replica sketch of the Gyroid unit cell
- Step 2) Create a surface unit of the gyroid
- Step 3) Pattern and thicken

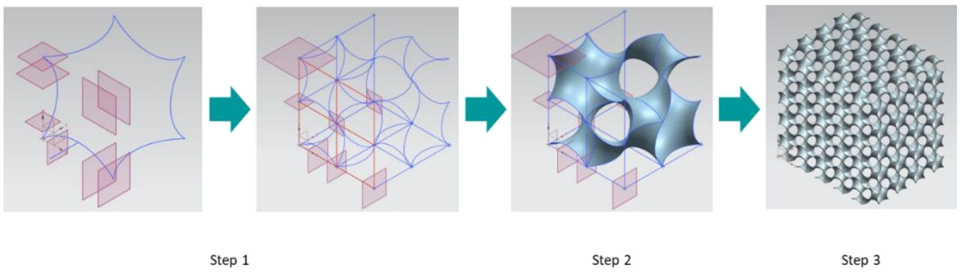


Figure 23 Workflow for creating non-conformal type Gyroid Lattice in NX

For conformal gyroid:

- Step 1) Create a replica sketch of the Gyroid unit cell in a sector shape
- Step 2) Create a surface unit of gyroid and pattern
- Step 3) Thicken the surface
- Step 4) Unit it with the model
- Step 5) If required, export it as .stl for 3D printing.

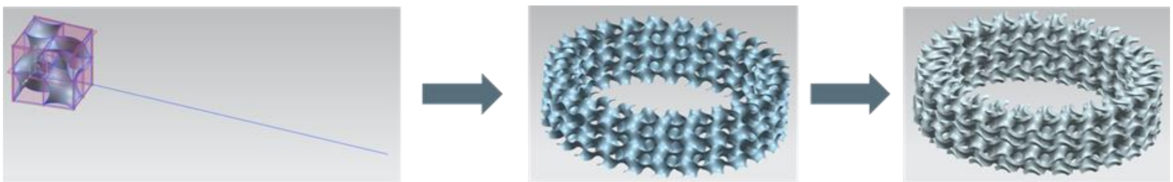


Figure 24 Workflow for creating conformal type Gyroid Lattice in NX

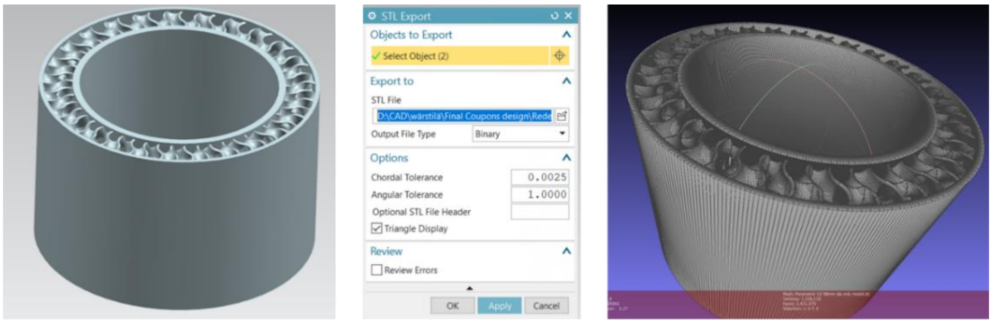


Figure 25 Workflow for creating conformal type Gyroid Lattice in NX

For non-conformal Schwarz P surface.

- Step 1) Create a replica sketch of Schwarz P
- Step 2) Create a surface unit of Schwarz P
- Step 3) Thicken the surface
- Step 4) Pattern the model and unit

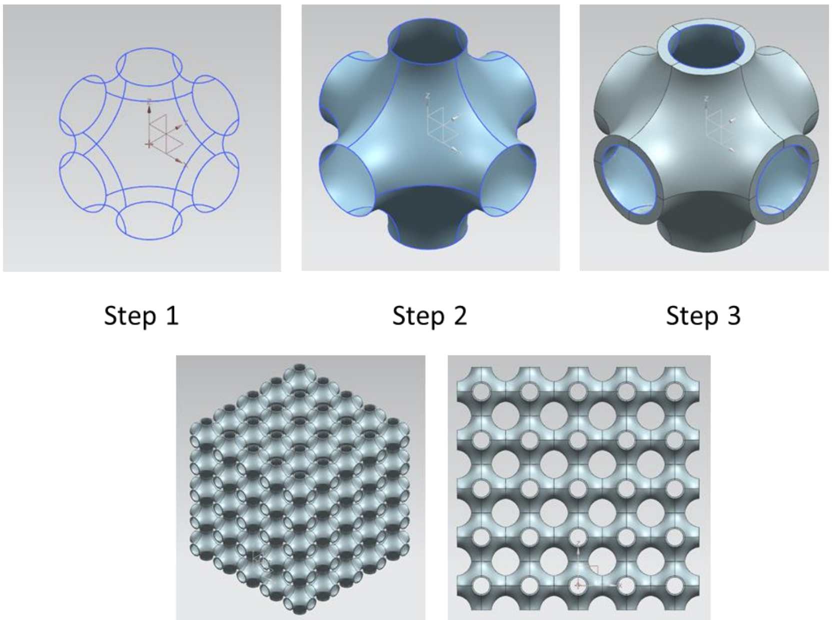


Figure 26 Creating Schwarz - P lattice structure in NX

The gyroid structures created are solid body models, hence it can be exported as solid-body formats like .step or .iges. Another advantage of this approach of creating such structures is that the structures can be parametrized.

nTopology- Element, nTop Platform

nTopology combines both parametric and implicit functions to generate complex lattice structures. The workflow is straightforward, and the software allows importing the solid structures which can be used as boundaries or areas to generate lattice structures. Element performs better than NX in terms of lattice generation and modification, allowing the generation of lattices of variable thickness and allowing the export of the lattice generated as a solid body. However, this feature partially is limited to the type of shapes. The following figures show the steps involved in creating lattice structures.

Creating Lattice structure

The workflow for generating a Lattice structure using nTopology Element is shown in Figure 27. The steps are similar to that of Siemens NX, but the Element has features that can generate variable thickness lattices. The thickness distribution is controlled by the Modify option. The Modify option allows creating reference variables like points, vectors, or surfaces to control the thickness distribution.

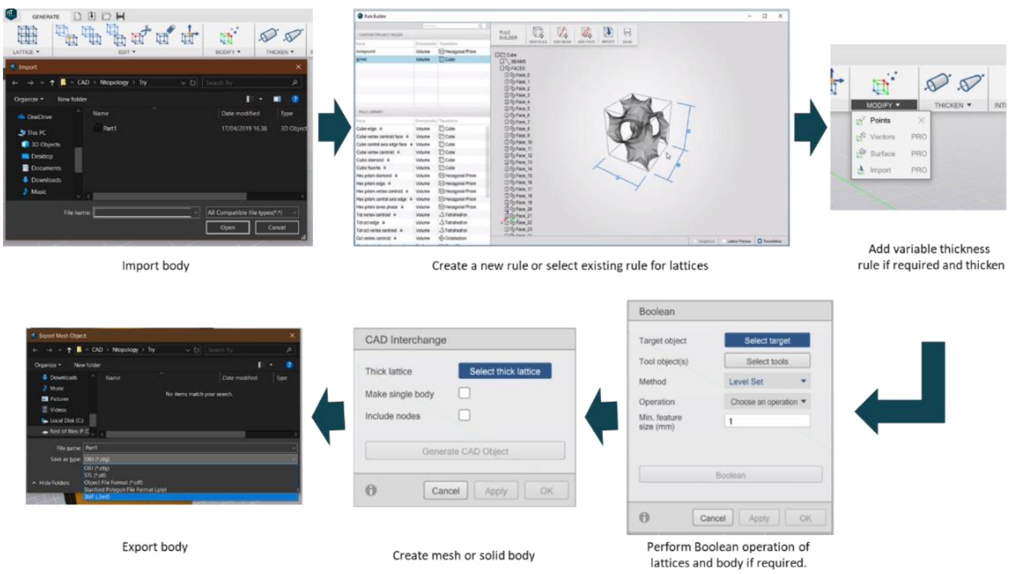


Figure 27 Lattice Generation using nTopology Element

Creating a Gyroid /Minimal surface

To generate minimal surfaces, the nTop platform by nTopology is used. nTop platform is an implicit modeling tool that generates shapes based on the inbuilt mathematical functions. To activate these functions respective commands are used. The workflow for creating Gyroid/Minimal surface as shown in Figure 28 in the nTop Platform is as follows.

- Step 1) Import or create a solid body for reference.
- Step 2) Create a nTop body from the imported reference body.
- Step 3) Create a TPMS gyroid body by using command TPMS or by clicking on the TPMS icon in the GUI by considering nTop body as a reference.
- Step 4) Create a mesh body from the nTop body (which is the Gyroid TPMS body now)
- Step 5) Export the mesh body created as the required format

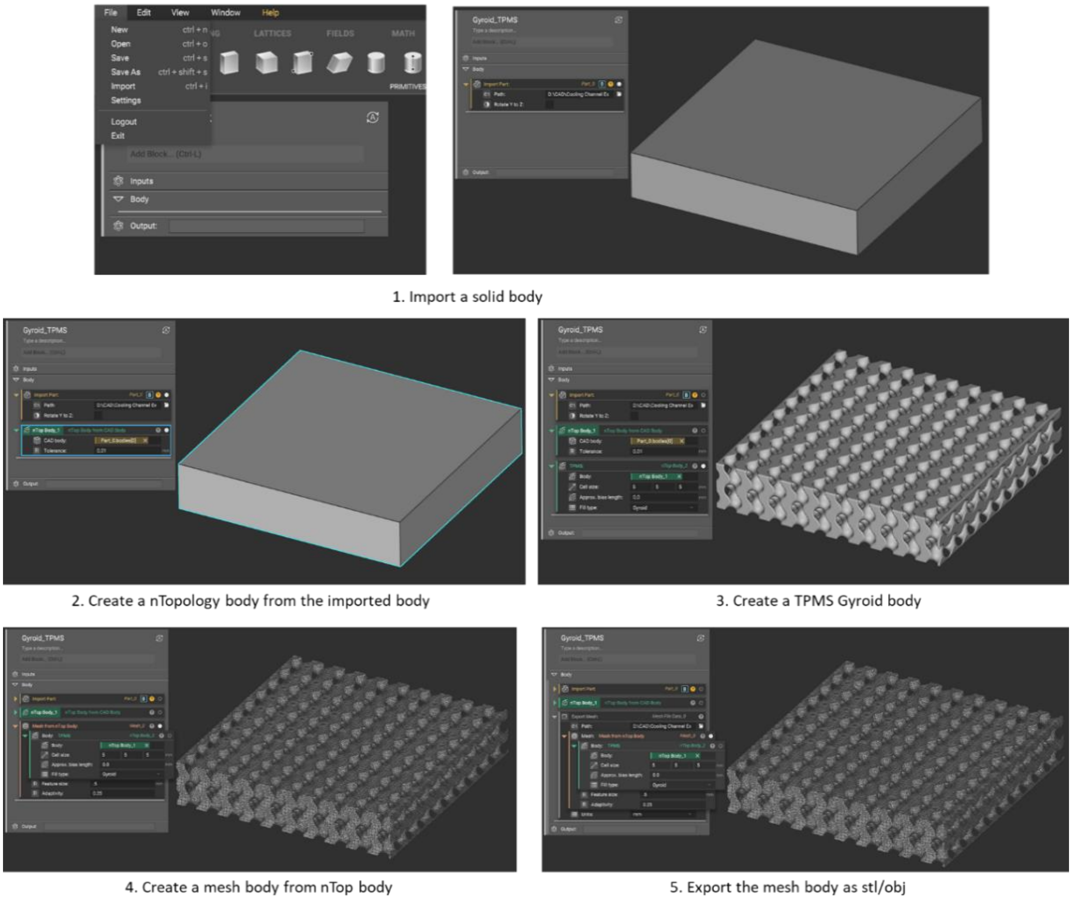


Figure 28 Gyroid/Minimal surface body generation using nTop Platform

KDsurf software:

KDsurf (Taha, 2015) is a software program that allows creating surfaces using mathematical equations. It has over 20 different surfaces that can be exported as an object file format and then imported into the blender or other modeling software to create a surface body. The advantage of this software is that it does not require any additional coding. Rather, by entering their equations, the surfaces can be generated and then exported. The steps to generate the gyroid surface are shown in Figure 29.

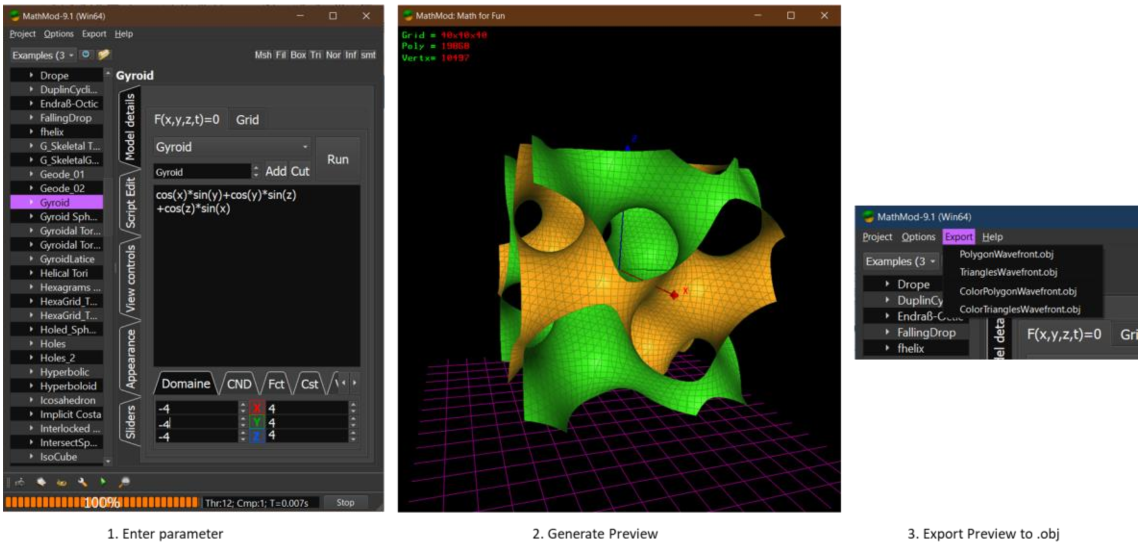


Figure 29 Gyroid/Minimal Surface generation using KDsurf

MATLAB:

The minimal surfaces like Gyroid surfaces can be created using MATLAB by solving their equations. The code as shown in Figure 30 was taken from a code posted by a user online (3Dprinting, 2018). The code is made available in the appendices section. The generated surface can be exported into software like Blender or Element Pro and lattices can be created. These lattices can generally be exported as surface files. There are several such surfaces and their equations are made available on the website https://math-curve.com/surfaces.gb/surfaces.shtml.

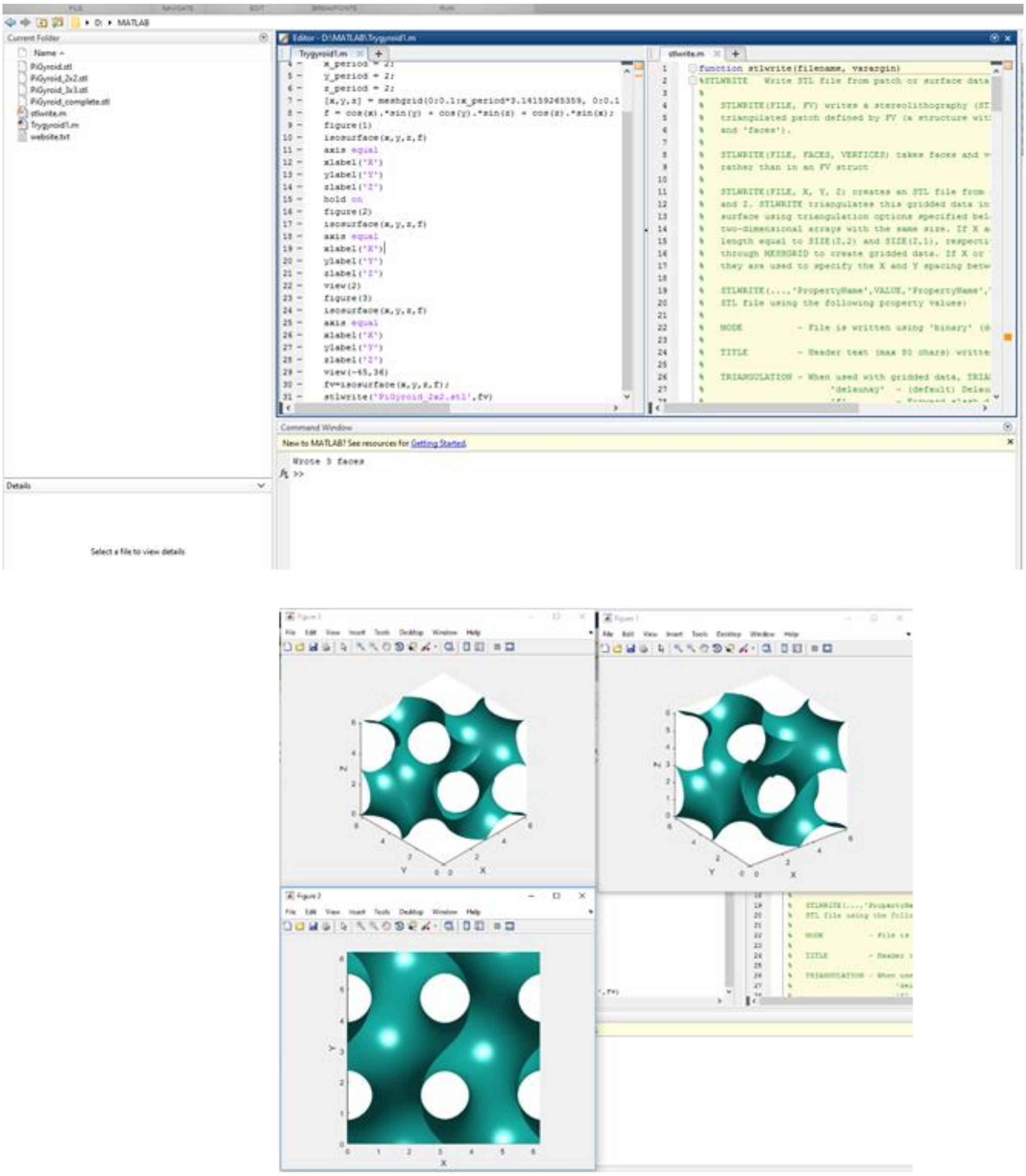


Figure 30 Gyroid generation using MATLAB

4.2 Heat transfer analysis workflow

This section of the thesis will discuss the workflow used for the thermal simulation of the component chosen for design in the case study. The main goal of the simulation was to calculate the physical conditions required for cooling the components and maintaining the temperature as mentioned in the deliverables. The software used for conducting CHT simulation was Ansys AIM. The remarks from CHT simulation of different types of lattices used in the case study are tabulated in Table 14.

The computer system used to simulate heat transfer in the structures had the following hardware specifications,

Table 13 Hardware specification used for conducting CHT analysis

Operating System	**Windows 10**
Processor	**Intel – i7 – 9th Generation**
RAM	**32 GB**
Graphics Card	**Nvidia GeForce RTX 2070**

4.2.1 Reports from Computer Simulation of the structure

Table 14 Reports from CHT Simulation of the lattice structure

Structure Name	Analysis Type	Software	Time Taken	Remarks
Gyroid (.step file as Input)	Solid – Fluid Heat transfer (Conjugate Heat Transfer)	Ansys AIM (Student Version)	10 hours	Successful simulation
Pin Fins (Lattice) (.step file as Input)	Solid – Fluid Heat transfer (Conjugate Heat Transfer)	Ansys AIM (Student Version)	45 minutes	Successful simulation
Lattice Structures (.step file as Input)	Solid – Fluid Heat transfer (Conjugate Heat Transfer)	Ansys AIM (Student Version)	1 Hour	Successful simulation
Face type lattice (.stl file as Input)	Solid – Fluid Heat transfer (Conjugate Heat Transfer)	Ansys AIM (Student Version)	8 hours	Successful simulation (Applying Meshing and Boundary conditions were comparatively difficult)
Cellular lattice (.stl file as Input)	Solid – Fluid Heat transfer (Conjugate Heat Transfer)	Ansys AIM (Student Version)	3 hours	Successful simulation (Applying Meshing and Boundary conditions were comparatively difficult)
Gyroid TPMS (.stl file as Input)	Solid – Fluid Heat transfer (Conjugate Heat Transfer)	Ansys AIM (Student Version)	--	The simulation did not go through. Windows Performance indicated 100 % use of RAM

4.2.2 Workflow for Simulating Heat transfer using Ansys AIM

The steps involved in workflow for simulating the workflow in the Ansys AIM software is as follows,

- Step 1) Choose the Fluid-Structure Heat Transfer module.
- Step 2) Import the geometry with a solid and fluid body.
- Step 3) Set the meshing parameters
- Step 4) Define the physics region for fluid and solid
- Step 5) Define the fluid flow and thermal boundary conditions region
- Step 6) Define the interface conditions between solid and fluid body
- Step 7) Review the boundary condition and Run the simulations
- Step 8) Generate the results

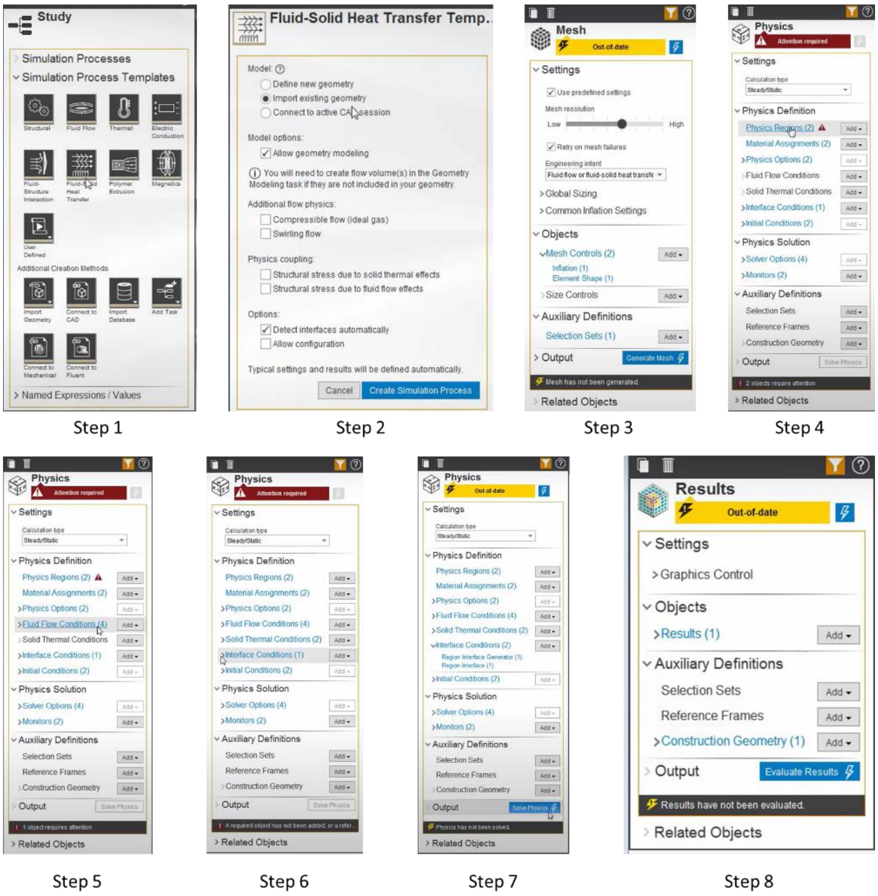
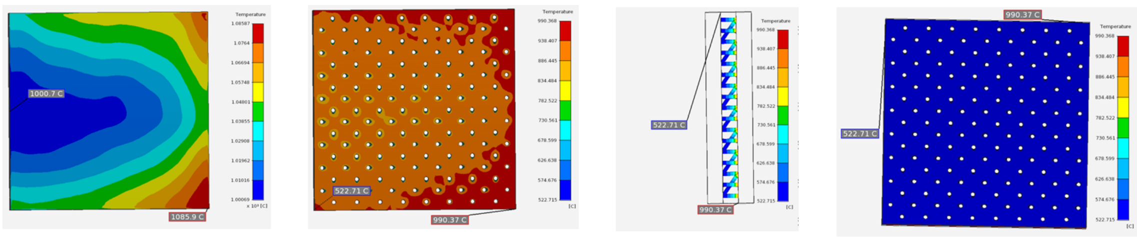


Figure 31 Workflow for simulating conjugate heat transfer using Ansys AIM

- Step 9) Analyze the results



Temperature near the Heat source | Temperature near fluid and solid contact (bottom view) | Temperature near fluid and solid contact (side view) | Temperature near fluid and solid contact (top view)

Figure 32 Results generated in Ansys AIM post CHT simulation

4.3 Case Study Results

During the design process, there are several ideas and concepts which designers generate through their intuitions and research. In addition to this, different experiments/simulations are conducted to check the performance of these design concepts. When there are several different parameters, variables, and rules governing the design process, there is a good probability of uncertainties. These uncertainties may be in decision-making for design selection or methodology for conducting experiments and so on. To avoid these uncertainties and structure the processes in the design phase, DFSS methodology is implemented. This case study acts as an example of the integration of DFSS in the design process.

Jet engines are designed to be lightweight and gain maximum performance with the lowest overall weight in order to get better fuel efficiency. Additive Manufacturing has enabled manufacturing lightweight structures with most complex geometries, thus making it ideal for manufacturing jet engine components. Although Design for AM is not a fully mature method, there have been many kinds of research in this area. The goal of this case study is to develop a workflow for the design for AM for a case of designing a heat management solution. The physical conditions the design experiences resemble the combustion chamber of a Jet Engine, although the geometry is modified to avoid any hassles due to intellectual property rights. The final goal is to maintain a temperature of 590 c near the heat transfer region which transmits 35.4 kW of heat towards the outer region. For the cooling purpose, air inlet at 80-82 bars can be given as input at 500 c. As discussed earlier in the literature review section, extended surfaces are an ideal choice for heat transfer-based applications.

4.3.1 **Identify Phase**

Project Summary

Project Name: Heat Management Solution

Project Overview: The purpose of this project is to develop a heat management solution considering the advantages of Additive Manufacturing. Secondly, investigating right amount of coolant and physical condition required to achieve it.

Project Statement: The design model is a hypothetical geometry of the bottom part of a singular combustion chamber for turbofan application, including a portion of the outlet pipe feeding the exhaust gases to the turbine inlet. For typical applications, the cooling systems are manufactured using non-AM methods, hence the design is more generic geometry which can be manufactured in non-AM methods. This design project aims to create non generic shapes by considering all the best available simulation software to analyze its heat transfer performance its and advantages of AM which enables the manufacturability of these non-generic shapes designed.

Customers/Stakeholders: The design concept will be handled in general to the concurrent design process phase. (Although, here the stakeholder/customer is the author of the thesis)

Critical to Satisfaction (CTS): There are two major CTSs: One, Achieve a heat distribution of 590 c near the heat source region. Two, achieve this with minimum weight.

Goal of the Project: The goal of the project is to make best use of the advantages of the AM in terms of mechanical design to achieve the CTSs and to determine the right physical condition required to achieve this.

Scope of the Project: The scope of the project is to design the solution only by considering heat transfer load condition, therefore all the other structural conditions are neglected. Furthermore, the project limits the scope at developing a workflow for design and understanding DfAM in design critical applications as such.

Project Plan

DFSS is designed to divide the whole process into activities under several phases and concentrate on each phase of activities for better efficiency. The DFSS methodology chosen here is IDDOV, and the whole design process is structured and disciplined through phases and gates in the Project Plan. The project plan structure consists of four phases along with four gates. Each phase is implemented with the checklist of activities and tools to be involved towards the end of the respective gates. The four phases are chosen, and their respective phases are as shown in Figure 33.

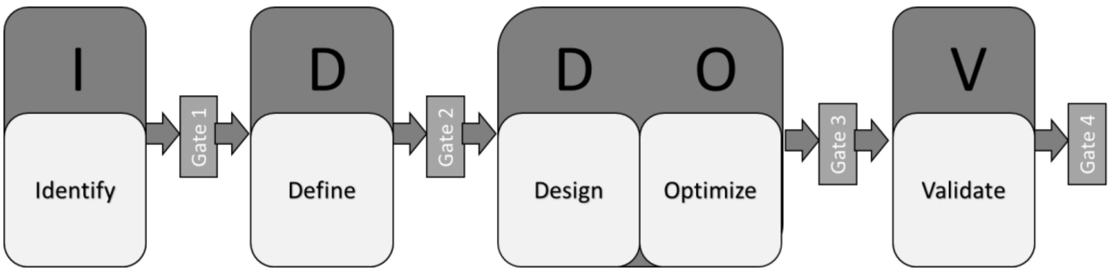


Figure 33 DFSS - IDDOV phase roadmap of this project

<u>Phase 1/Gate 1: Identify:</u>

In this phase/towards the end of this gate, the design process will develop a project charter, create a roadmap, develop a project plan.

Checklist: Project plan, Project Charter, Gantt Chart.

<u>Phase 2/Gate 2: Define</u>

In this phase/towards the end of this gate, the design process will focus on understanding the customer need, perform analysis on critical requirement factors, define the requirements and software needed for further phases.

Checklist: Voice of the customer, Customer Requirement form, Customer Requirement Ranking, Analytic hierarchy process (AHP).

Phase 3/Gate 3: Design and Optimize

In this phase/towards the end of this gate, the design process will create designs, conduct analysis, and check for the requirement of the customer. As well as, the design will undergo optimization to develop the best design solution as per the requirement to satisfy the customer needs.

Checklist: Brainstorming, Concept Design selection – Pugh's selection matrix, Heat transfer analysis.

Phase 4/Gate 4: Validate

In this phase/towards the end of this gate, the design process will cross-refer the design requirements with the designed solution to assess if the solution completely satisfies the requirement.

Checklist: Manufacturability test, Concept verification scorecard

Project Schedule:

The project schedule/Gantt chart developed to keep track of the activities involved, their timeline, and check and ensure their progress is as planned. This design project is scheduled over a period of 6 months, with the majority of the project time spent on performing design and computer simulation. Figure 34 shows the activities planned in each phase and their schedule.

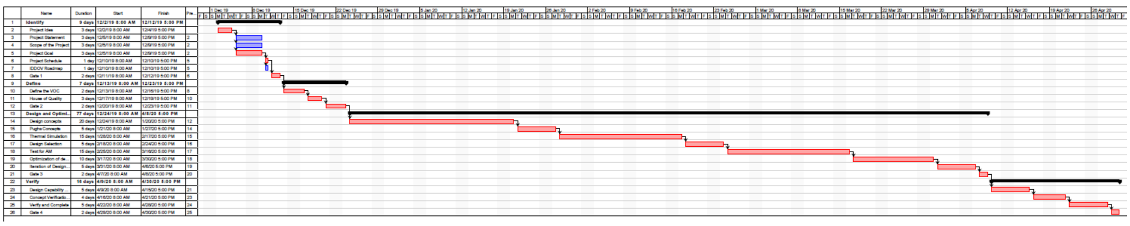


Figure 34 Project Schedule - Gantt Chart

4.3.2 Define Phase

Voice of customer (VOC)

To implement the VOC, a Requirement form was designed which could collect requirements of the customer. It must be noted that since the customer here is the author itself, the required form is self-answered. Table 15 shows the requirement form. Considering the major requirements from the other existing researches and developmental projects the important characteristics of similar projects are also given as pre-filled criteria.

The key take-aways from the requirement forms were,

- Strong features of customization should be visible
- The design must be lightweight
- Maximum heat transfer with a minimum overall weight
- Must consider the advantages of the AM
- Must consider Manufacturability for AM
- Must explore software options available for conducting simulation

Customer Requirement form:

Table 15 Customer Requirement Form

<table>
<tr><td colspan="3">Customer Name: Tharanath</td><td>Date: 12/12/2020</td></tr>
<tr><td colspan="3">Project Name: Design of Part X for AM</td><td></td></tr>
<tr><td colspan="4">Project Summary: This project aims to develop a heat management solution considering the advantages of Additive Manufacturing. Secondly, investigating the right amount of coolant and physical condition required to achieve it.</td></tr>
<tr><td colspan="4">Additional Information: The cooling is achieved by passing coolant over the cooling structures. The coolant used is pressurized air.</td></tr>
<tr><td colspan="4">Essential Design Requirements:</td></tr>
<tr><td>▪ Good Heat Transfer Ability, achieve a temperature of 550 c near the heat source zone</td><td colspan="2">▪ Investigate the right physical condition</td><td>▪ Investigate the best physical structures for the purpose</td></tr>
<tr><td>▪ Good AM print quality</td><td colspan="2">▪ Develop Workflow for design</td><td>▪ Investigate the AM Manufacturability of the design.</td></tr>
<tr><td>▪ Identify suitable software for Designing the structures</td><td colspan="2">▪ Identify suitable software for the Computer Simulation</td><td>▪ Identify suitable software for checking manufacturability through AM</td></tr>
<tr><td colspan="4">Expected Design Features:</td></tr>
<tr><td colspan="2">▪ Minimum weight without costing the performance</td><td colspan="2">▪ Organic/Customized design of structures</td></tr>
<tr><td colspan="4">Other information:
Information about the coolant used.</td></tr>
<tr><td>Material:
Compressed Air with density 56.2 kg/m^-3</td><td colspan="2">Inlet Pressure:
81-82 bar
Expected outlet Pressure:
80 bar</td><td>Inlet air temperature: 300 – 500 C</td></tr>
<tr><td colspan="4">Expected duration of the project: 6 months</td></tr>
<tr><td colspan="4">Sign:
Tharanath</td></tr>
</table>

Customer requirement ranking:

The customer requirement ranking as shown in Table 16 is used to understand the most important features to be integrated into the design when there are design challenges ahead. These most important factors are considered as Critical to Satisfaction Factors (CTS):

Table 16 Customer Requirement Ranking

Rank	Customer Requirement	Importance
1	Maximum heat transfer with a minimum overall weight	5
2	Must explore software options available for conducting simulation	5
3	Must consider Manufacturability for AM	5
4	Develop a workflow for designing the models	4
5	Strong features of customization should be visible	3
6	The design should be lightweight	3

Simulation Software selection Using AHP

Simulation plays an important role in determining which design concept is better compared to the rest. To determine the performance of the designs in terms of heat transfer, the design concepts must go through conjugate heat transfer simulation. The designs which reflect the required physical conditions as per the customer is chosen as the best design concept. The AM manufacturability test is conducted after the selection of the best design. The software selection is performed using a free Analytic hierarchy process (AHP) analysis tool (Goepel, 2018a).

The following criteria were selected for choosing the right simulation software.

1. Free to use/ Student license available
2. Supports Conjugate Heat Transfer Simulation

3. Easy to setup simulation
4. Requires more computational power
5. Cloud-based/Offline based
6. Reputation and Recommendation/Userbase
7. Support / Training Videos/ Reference Manuals

An AHP analysis was conducted to determine the ranking of the selection criteria through the online AHP tool. The results from AHP analysis are shown in Figure 35. Therefore, the top three priorities for software selection are categories 3, 1, and 2, respectively.

Priorities

These are the resulting weights for the criteria based on your pairwise comparisons:

Cat		Priority	Rank	(+)	(-)
1	Free to use/ Student license available	15.1%	2	12.2%	12.2%
2	Supports Conjugate Heat Transfer Simulation	13.4%	3	6.4%	6.4%
3	Easy to setup simulation	37.3%	1	24.8%	24.8%
4	Requires more computational power	8.8%	5	7.9%	7.9%
5	Cloud based/Offline based	5.9%	7	5.9%	5.9%
6	Reputation and Recommendation/Userbase	7.0%	6	11.0%	11.0%
7	Support / Training Videos/ Reference Manuals	12.5%	4	12.2%	12.2%

Decision Matrix

The resulting weights are based on the principal eigenvector of the decision matrix:

	1	2	3	4	5	6	7
1	1	1.00	1.00	2.00	9.00	0.33	1.00
2	1.00	1	1.00	2.00	2.00	2.00	2.00
3	1.00	1.00	1	9.00	9.00	9.00	9.00
4	0.50	0.50	0.11	1	5.00	4.00	0.25
5	0.11	0.50	0.11	0.20	1	2.00	2.00
6	3.00	0.50	0.11	0.25	0.50	1	0.14
7	1.00	0.50	0.11	4.00	0.50	7.00	1

Figure 35 AHP analysis for selecting the best simulation software.

After conducting AHP analysis, the simulations software was searched using google, the keywords used were “free CHT transfer software, Conjugate heat transfer software, Fluid – solid heat transfer, heat transfer analysis”. And then results were categorized and compared to each other according to the criteria chosen earlier during the AHP. Based on the comparison Table 17 and the priorities from the AHP analysis, the better choice for the simulation task in this thesis is Ansys AIM.

Ansys AIM:

Ansys AIM (Ansys, 2016) is a computer simulation software which allows performing computer simulation in a very easy to use environment. The most important feature of the software is simplifying the simulation workflow for non – expert engineers to conduct Multiphysics simulation through the task-based workflow.

The workflow of the Ansys AIM software is as follows,

- Step 1: Import the geometry file for conducting a simulation.
- Step 2: Select the type of simulation to be performed
- Step 3: Select the characteristics of the simulation
- Step 4: Enter the parameters involved in the simulations on the respective body or phases
- Step 5: Modify the simulation parameters and meshing parameters if required and conduct simulation
- Step 6: When the simulation is complete, evaluate the results by selecting the type of results and respective faces or body region.

Table 17 Comparison of Computer Simulation Softwares

Sl No.	Software Name	Free to use/ Student license available	Supports Conjugate Heat Transfer Simulation	Easy to setup simulation	Requires more computational power	Cloud based/ Offline based	Reputation and Recommendation/Userbase	Support / Training Videos/ Reference Manuals
1	Ansys AIM	YES	YES	EASY	MEDIUM	OFFLINE	VERY GOOD	GOOD
2	Ansys Workbench – Fluent/CFX	YES	YES	MEDIUM	HIGH	OFFLINE	VERY GOOD	GOOD
3	Altair Hyperworks	YES	YES	MEDIUM	HIGH	OFFLINE	VERY GOOD	GOOD
4	SimScale	YES	YES	MEDIUM	LOW – (ONLINE)	Cloud based	GOOD	GOOD
5	Cosmol Multiphysics	NO	YES	MEDIUM	HIGH	OFFLINE	VERY GOOD	GOOD
6	Autodesk CFD	YES	YES	YES	MEDIUM	Cloud based/ Offline based	GOOD	GOOD
7	Siemens Star CCM+	NO	YES	MEDIUM	HIGH	OFFLINE	GOOD	GOOD
8	Symscape	NO	YES	YES	MEDIUM	OFFLINE	MEDIUM	AVERAGE
9	Elmer –by csc.fi	YES	YES	HARD	HIGH	OFFLINE	MEDIUM	AVERAGE
10	Cast3M	YES	YES	HARD	HIGH	OFFLINE	MEDIUM	AVERAGE
11	OpenFoam	YES	YES	HARD	HIGH	OFFLINE	GOOD	GOOD

4.3.3 **Design and Optimize Phase**

The design stage focuses on developing practical solutions to the problems identified in the identify and define stage. The designer looks into available solutions for inspiration or develops own solutions and tests the solution for its performance. The design process starts with concept generation through concept generation techniques like brainstorming and comparison of the existing research. Since the theory behind the heat transfer is already discussed in section 2.5, we shall move directly to the concept design phase.

Concept generation

Concept 1 - Parametric design (Pin Fins):

Parametric designs are generally designed using Traditional CAD software. The manual effort put into the design is considerably more when compared to the rest of the designs. Concept 1 is a parametric design commonly known as Pin Fins. This design has been one of the most preferred extended surface cooling designs because of its high surface area and manufacturability. Another advantage is the files exported can be of solid surfaces, which allows the workflow of the Computer Simulation to be less hectic and comparatively less time-consuming. The advantages of solid models over triangulated surface models like .stl are discussed in the literature in section 2.4. In addition to this, the parameters can be easily changed even after saving the file. Therefore, after each simulation, if there is a requirement for the change of parameters then it can be done easily without hassles. The Pin Fin design chosen here is of variable thickness. This choice helps to create better turbulence which partially helps in increasing heat transfer between the Pin Fins and the coolant. Figure 36 shows the variable thickness Pin Fine type lattice structure.

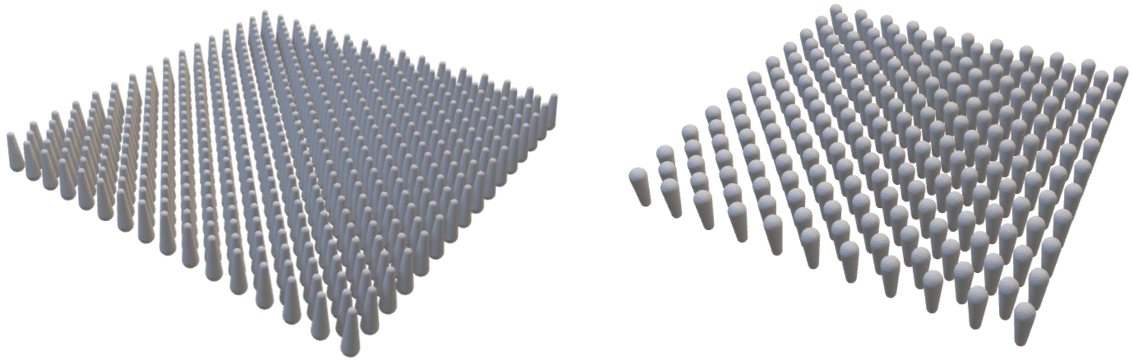


Figure 36 Variable thickness Pin Fin design concept - Parametric design type

<u>Concept 2 - Non – Parametric Design (Cell lattice type and Face lattice types):</u>

The concepts shown in Figure 37 show Lattice type designs, which are non-parametric as the modification of the designs are not possible after the creation of the model and are usually created using lattice generation software rather than manual design. Although, this design method allows creating different models inspiring organic shapes and structures. Since the designs can be complex and more bodies can be generated in the given area, the surface area compared to parametric designs are higher. The lattice generation software allows controlling of parameters during the generations, hence after the simulations, if there is a need for change in parameters then a new model with changed parameters can be generated. The files are usually exported as triangulated surface models like .stl files, which makes it harder for simulation setup.

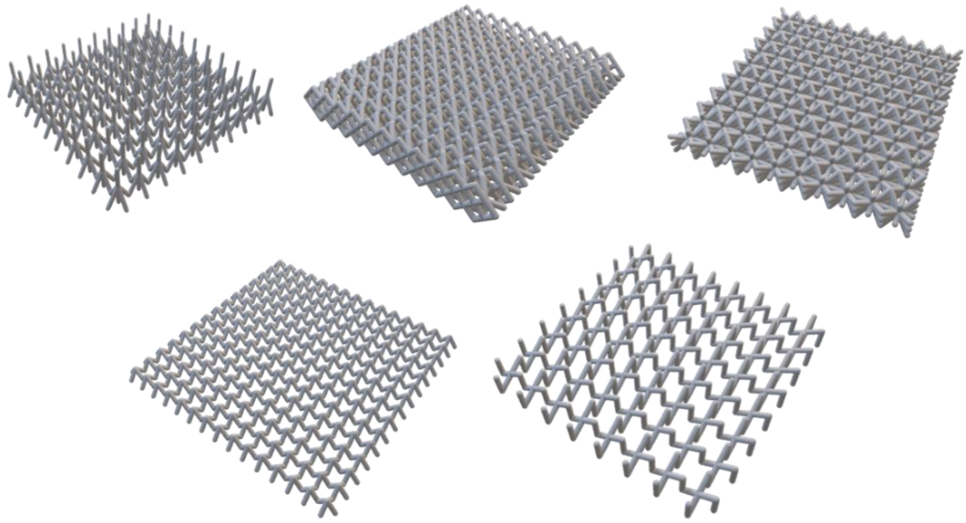


Figure 37 Cell Type Lattice structures

Figure 38 shows the face type of lattices. These types of structures are very effective in controlling the flow and creating turbulence. Like the cell type lattices, the parameters need to be controlled during the generation, since the structures are complicated the patterning method of parametric designs can become tiresome and time consuming for designers. Hence, these structures need to be generated using special software like nTop Platforms.

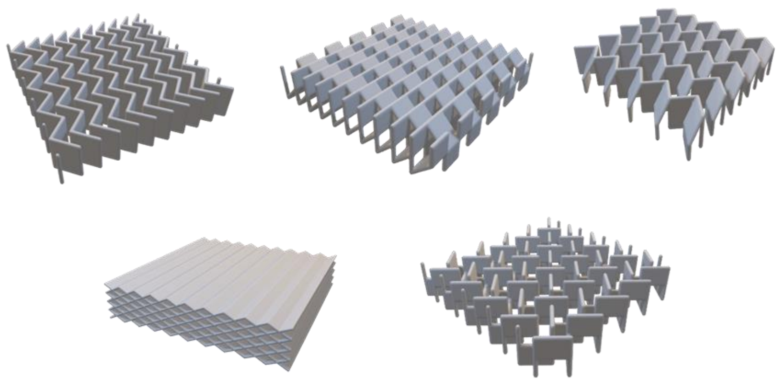


Figure 38 Face type lattice structures

Concept 4: Implicit Concepts Design (Minimal Surfaces):

Implicit structures are generally generated using software specially designed for this such as nTop Platform, Grasshopper (for Rhino), Blender, etc. These structures are created using mathematical equations and then combined with solid surfaces using Boolean operations. The surface areas are usually larger in this kind of design, although the files can only be exported as triangulated models like .stl files. Figure 39 shows the Gyroid TPMS minimal surface lattice generated by the Implicit design method.

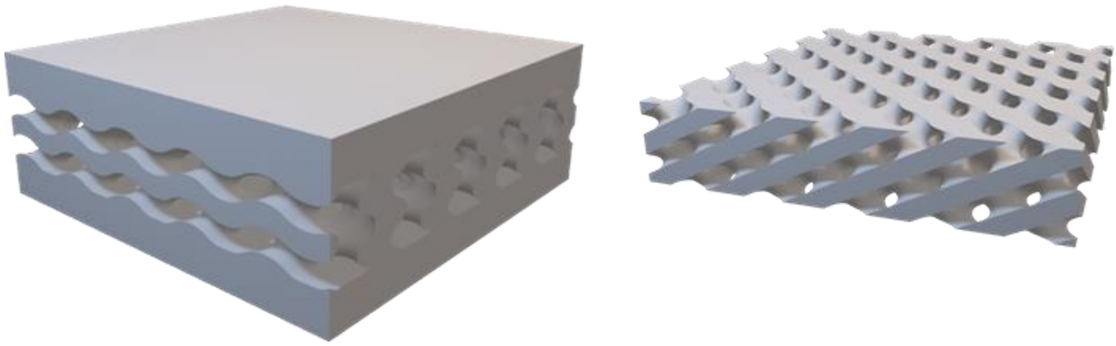


Figure 39 Gyroid TPMS type Minimal surface lattices

Pugh Concept selection

All the concepts generated look promising, but not all types of designs can be used for the next stage in the design phase. Therefore, the best suitable concepts need to be selected. Pugh Concept selection is the best tool for this kind of challenge. To continue with the Pugh concept section, the most important design requirements or characteristics which are needed for the final design or the next stage is selected. And then, one of the design concepts is considered as a candidate concept which will be compared with the rest of the design concepts based on the selected characteristics/requirements. The concept which receives few minuses and more pluses is considered as the Ideal concept. Table 18 shows Pugh's concept selection matrix and how the other concepts performed when compared with the candidate concept. Since the candidate concepts outperform other concepts, we shall proceed with the candidate concept i.e., Parametric design.

Therefore, for further designs, the Pin Fin design shall be adopted, and the thermal simulations will be conducted.

Table 18 Pugh's Concept Selection Matrix

	Concepts			
Criteria	**Parametric Design (Pin Fin)**	**Non-Parametric (Cell Lattice type)**	**Non-Parametric (Face Lattice type)**	**Implicit/Minimal Surfaces**
Easy to Create	**Candidate Concept**	**0**	**0**	**0**
Easy to Export		**0**	**0**	**0**
Easy to Simulate		**-**	**-**	**-**
Easy to Modify		**-**	**-**	**-**
Large Surface Area		**0**	**+**	**+**
Numbers Better (+)		**0**	**1**	**1**
Number Worse (-)		**2**	**2**	**2**
Number Same (0)		**3**	**2**	**2**

Figure 40 shows the selected concept - Pin Fins around the heat transfer region. To conduct the simulation, a layer of a solid body is created around these pins which will act as a region for fluid flow.

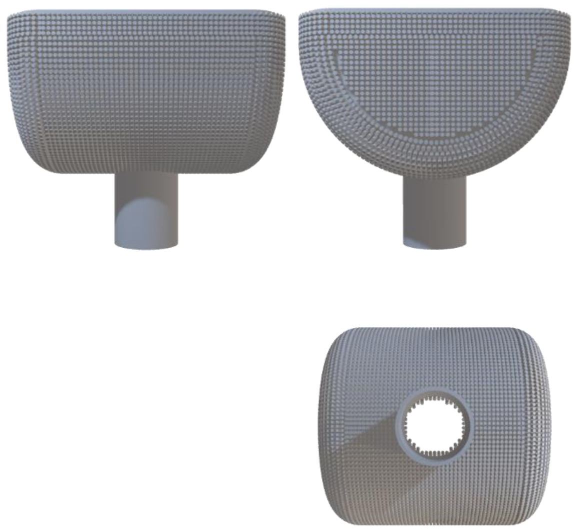


Figure 40 Candidate Concept (Pin Fins) around the heat transfer area.

Thermal Simulation

The next step in the design phase is conducting simulation to evaluate the performance of the concept model for its heat transfer performance. Figure 41 shows the workflow for the thermal analysis. The type of thermal analysis chosen here is Conjugate heat transfer using the student version of Ansys AIM. This software is chosen for its intuitive interface and ease of setting up a simulation. To improve the speed of simulation a square block of 50 mm x 50 mm x 4 mm is considered, and the extended surface is created over it for another 4 mm, which is followed by the same 4mm thick wall. To better understand the behavior of the model, the pins are placed with a strategy that is governed by the parameters as shown in Table 19.

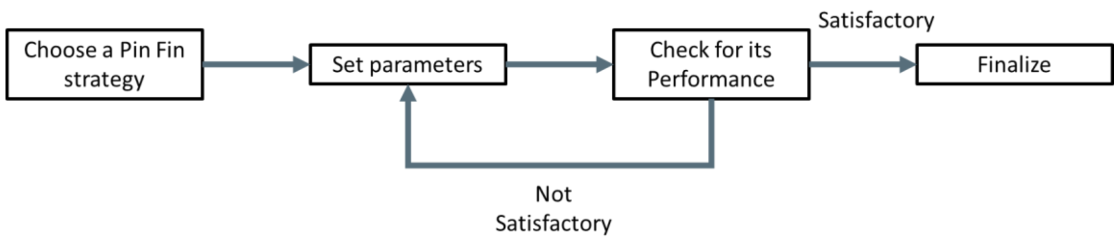


Figure 41 Thermal Analysis Workflow

If the results generated are matching the requirement, then the design chosen for the analysis is finalized. If the results do not match the requirements, then the parameters are modified according to the strategy chosen, and the simulation is conducted until the requirements are met. The strategy for the Pin Fins diameter is chosen without any prior analysis. The approach chosen to be used here is trial and error. During initial flow simulation, maintaining the flow between the pins with a minimum gap of 1 mm at 1 bar pressure difference showed better flow around the pins. Hence, the gap maintained between the pins is chosen to be more than 1 mm. The lattices are placed with a minimum distance to facilitate a smooth flow of coolant between them and create a minimum boundary layer. The flow was analyzed using flow simulation and the minimum distance between them was identified to be more than 1.5 mm. For this study, the minimum vertical distance (V) was maintained at 1.5 mm and the minimum horizontal (H) distance is maintained at 2 mm. The initial minimum and maximum diameter were chosen to be 1 mm and 1.5 mm, respectively. The maximum and minimum diameter of the variable lattices is increased by 0.5 mm for 6 different trials. The goal is to predict the best physical condition to achieve the required temperature near the heat source.

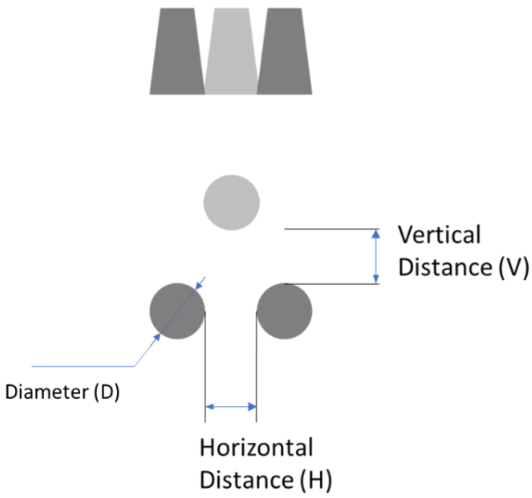


Figure 42 Lattice placement for the CHT simulation

Table 19 Pin Fin Placement Strategy

Strategy Designation	Horizontal distance (H)	Vertical Distance (V)	Truncated Cone	
			Maximum Dia.	Minimum Dia.
A	2	1.5	4	3.5
B	2	1.5	3.5	3
C	2	1.5	3	2.5
D	2	1.5	2.5	2
E	2	1.5	2	1.5
F	2	1.5	1.5	1

Simulation Setup:

The simulation setup is as shown in the Figure 43 below. The air is passed in the inlet, which is expected to dissipate the heat from the body as it passes out through the outlet. For each Pin Fin strategy, the conjugate heat transfer analysis is conducted with the coolant supplied at a pressure difference of 1 bar and 2 bar, temperature difference of 100 c in 3 steps raising from 300 to 500 c. The intention here is to understand which is the best match of pressure, temperature, and the diameter for obtaining the average temperature distribution of 590 c.

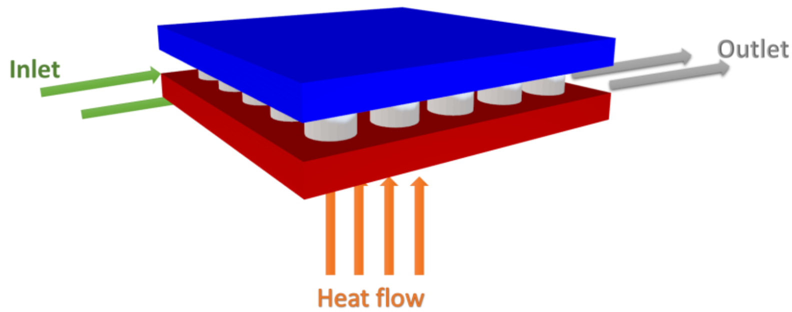


Figure 43 Simulation Setup

The boundary conditions for the setup is as follows,

- Coolant material: Compressed Air with a density of 56,2 kg m^{-3}
- Inlet pressure: 81 - 82 bar
- Inlet temperature: 300- 500 c
- Outlet Pressure: 80 bar
- Heat flow near the combustion chamber wall: 35.4 kW
- All the surfaces of the solid except the heat flow region are insulated. The faces except the inlet and outlet are set to be slip-free surfaces.
- The material of Solid body: Stainless Steel

Results from the Thermal Analysis

The results from each analysis are shown in the appendix in detail. But in order to understand the results better, pressure difference and temperature are paired. Therefore, we get around 6 pairs of the combinations and 36 observations corresponding to the pair and the average Pin Fin Strategy. The graphical representation of the data is easier when there are fewer variables, hence the combination pairs are used to represent the pairs of pressure difference and the temperature. The most significant observations from the results are nothing but the average temperature around the heat flow region in the model. Table 20 shows the temperature observation for different experiments conducted using the simulation software.

Table 20 Results from the Thermal Simulations

Combination names	Pressure Difference (bar)	Inlet Temperature (c)	Temperature neat Heat Source Zone for different Pin Fin Strategy (c)					
			A	B	C	D	E	F
P2_A	2	500	936	923	871	850	780	765
P2_B	2	400	865	862	825	815	694	669
P2_C	2	300	796	733	695	620	586	563
P1_A	1	500	1070	1010	982	906	829	812
P1_B	1	400	920	903	870	825	736	706
P1_C	1	300	850	859	805	760	652	627

The temperature near the heat source region for different simulation conditions is plotted in the column chart as shown in Figure 44. The results show that the combination of P2_C produces the lowest temperature near the heat source region. The P2_C combination corresponds to a pressure drop of 2 bar and temperature at the inlet as 300 c. Hence, this is the right combination of the pressure, temperature, and diameter we were aiming to find the research question. It can also be noted that the increase in surface area, a decrease in inlet temperature, and an increase in pressure drop, gives better results.

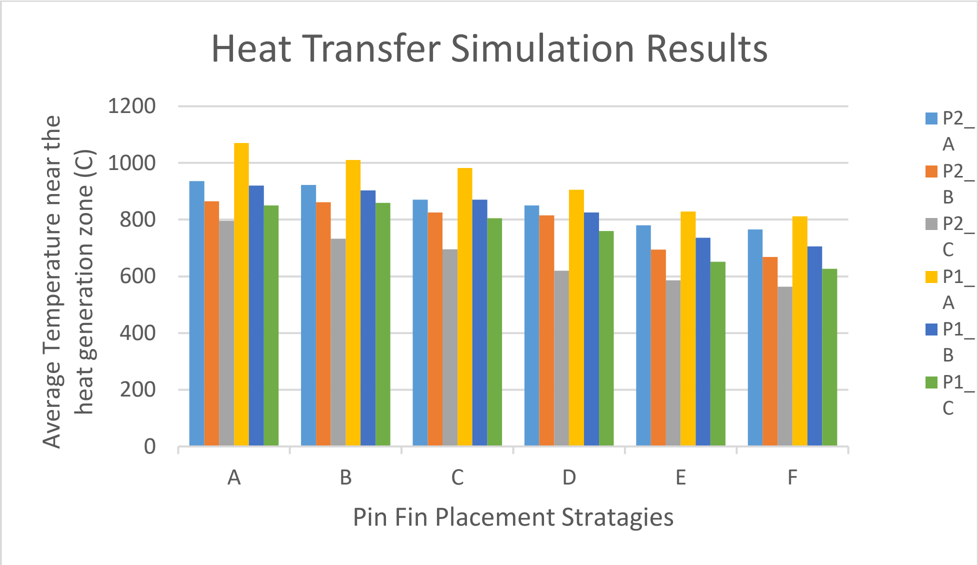


Figure 44 Chart comparing the results from the Thermal Simulations

<u>Design Selection:</u>

The Pin Fin design is the best choice made for designing the cooling solution structure for the design solution. The analysis shows a considerable decrease in the temperature near the heat source, which on the other hand without cooling might have reached a temperature of 4000 C. To narrow down the selection, the best choice of design is the Pin Fin design with F strategy and P2_C simulation configuration. The corresponding values of the selected design as follows,

- Inlet Pressure: 2 bar
- Outlet Pressure: 1 bar
- Inlet temperature: 300 c
- Pin Fin dimensions: Max. Dia – 1.5 mm, Min. Dia – 1 mm.

4.3.4 **Validate phase:**

The design selected from the heat transfer analysis is required to undergo a simulation test for manufacturability through Additive Manufacturing (AM) as well as the design must be assessed for its satisfaction of the Critical for Satisfaction (CTS) factors. The simulation of AM is done using the software Altair Inspire. The assessment of the design solution for the CTS factors is done using the concept verification scorecard.

Simulation of Manufacturability

The selected design will undergo a test for manufacturing using computer software called Altair Inspire. The amount of deformity, temperature distribution, stress distribution, and plastic strain experienced by the design specimen during the actual print can be calculated approximately. The following Table 21 shows the temperature distribution and deformity during the process. The Printer chosen was EOS_M_290 and the print material is AlSi10Mg. The goal here is to predict the conditions mentioned earlier, hence no design changes will be carried forward. Figure 45 shows the print specimen orientation and support generated.

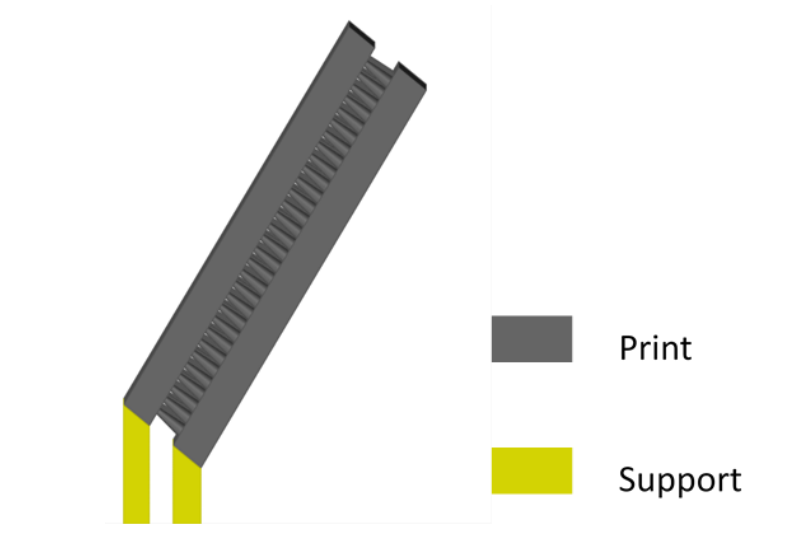
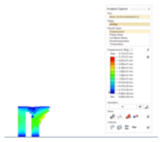
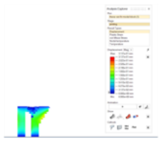
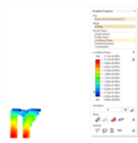
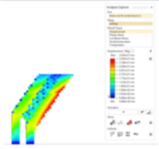
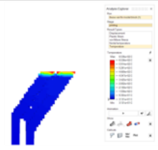
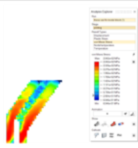
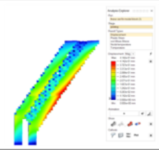
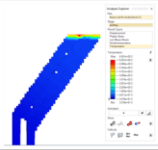
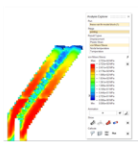
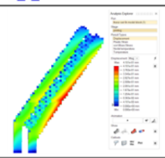
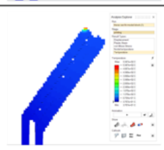
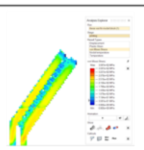


Figure 45 Print Orientation and Support preview using Altair Inspire

Table 21 shows the results from the thermo-mechanical simulation run through Altair Inspire. The simulation results show that there is a maximum deformation of .48 mm, the max temperature of 686 c, and max von mises stress of 359 MPa. The amount of deformity, von mises stress allowed are based on customer requirements or specifications. There is several other software like the Materialise Magics, Ansys, Autodesk Netfabb.

Table 21 Results from thermo-mechanical simulation using Altair Inspire

Percentage progress in Printing	Max Deformation (mm)		Max Temperature (c)		Von Mises Stress (MPa)	
25	0.31		686.4		314	
50	.34		653		284	
75	.41		659		273	
100	.48		538		359	

Concept verification Scorecard

The concept verification scorecard is developed to verify and validate the status of the critical to satisfaction factors. Table 22 shows the deliverables defined in the define phase and their status towards the end of the design phase. It can be noted that all the deliverables have a positive status.

Table 22 Concept Verification Scorecard

Deliverables		Status	Remarks
Design for Functionality	Required Temperature achieved near the heat source region	Achieved	The average temperature of 563 c achieved
	Investigated the required Physical Condition to achieve the required Temperature	Investigated Successfully	Inlet Pressure: 82 bar Outlet Pressure: 81 bar Inlet temperature: 300 c
	Investigated Manufacturability for AM	Investigated Successfully	Fit for manufacturing
Other Requirements	Develop Workflow for design	Developed	
	Identify suitable software for Designing the structures	Identified	Siemens NX. nTop Platform
	Identify suitable software for the Computer Simulation	Identified	Ansys Aim
	Identify suitable software for checking manufacturability through AM	Identified	Altair Inspire

4.4 Conclusions from the workflows for design and simulation

The CAD design (and modeling) of lattice structures and minimal surfaces by manual design require comparatively more man-hours compared to the generation of the design based on the parameters by a dedicated software or software feature. Although, the generated structures cannot be called a parametric model as these models cannot be modified later, instead a new set of the structure is to be generated and replaced with modified parameters. For the design process involving multiple iterations for the design and test cycle, the non-parametric models are not a good choice.

The computer simulations of both the parametric and non-parametric models were conducted. The models with a solid body and lesser triangulation were successful, however, models imported as .stl and having higher triangulation, the simulation time was comparatively higher. The simulation of the gyroid structure which was imported as .stl files did not go through. During the simulation of the Gyroid (.stl) file, the resource monitor feature of Windows 10 was run and analyzed, the RAM consumption was 100 %. Therefore, it was concluded that the meshing method chosen was wrong or the triangulation was higher which consumed more RAM resources. Since the goal of the case study was to find the right physical condition for achieving the temperature, the models which were easy to simulate were chosen.

5 Discussion and Conclusion

5.1 Conclusion

This study successfully demonstrated the challenges and limitations of the CAD and CAE software selected for the study. This is done by exploring the features of the selected software during the year of the thesis work. The important outcomes of the study are written in the following paragraphs. There might be some limitations in the study due to the author's knowledge and experience with the software used and the methodology followed for design and simulation. However, the weaknesses or criticism highlighted here are strong points for the engineering designers and industries to consider during their endeavor of product development or manufacturing with the help of Additive Manufacturing. And for the software developers, this would be a design challenge to accelerate their growth in the market by providing better design and simulation solutions tailored for AM processes.

Research questions,

1. What is the optimal workflow for designing a metal component for heat transfer produced by Additive Manufacturing technology?

The optimal workflow for designing a metal component, which is to be printed using AM is shown in the flow chart (Figure 46). The recommendation for the designer while designing a component are,

Before the design process,

- ❖ Collect the information about the printer used for manufacturing the component. This information is necessary while considering DfAM guidelines and principles.
  - ➢ The parameters of the design principles vary from printer to printer, although most types of printers follow similar design principles.
- ❖ Collect the information about the final requirements of the design.
  - ➢ For example: For a finer surface finish, the design may undergo post-processing. Therefore, knowing the final requirements helps the designer understand the support generation of the design and additional tolerances required.

During the design process,

❖ As per the results from this study, during the creation of the lattice structures, if the design needs to undergo computer simulations try to avoid designs that cannot be exported as solid file formats. Non-solid file formats are complicated to set up for computer simulations. And for designs that do not require computer simulation, the designers can choose the lattice structures which are generated with or without parameters and the file output can be either solid or non-solid.

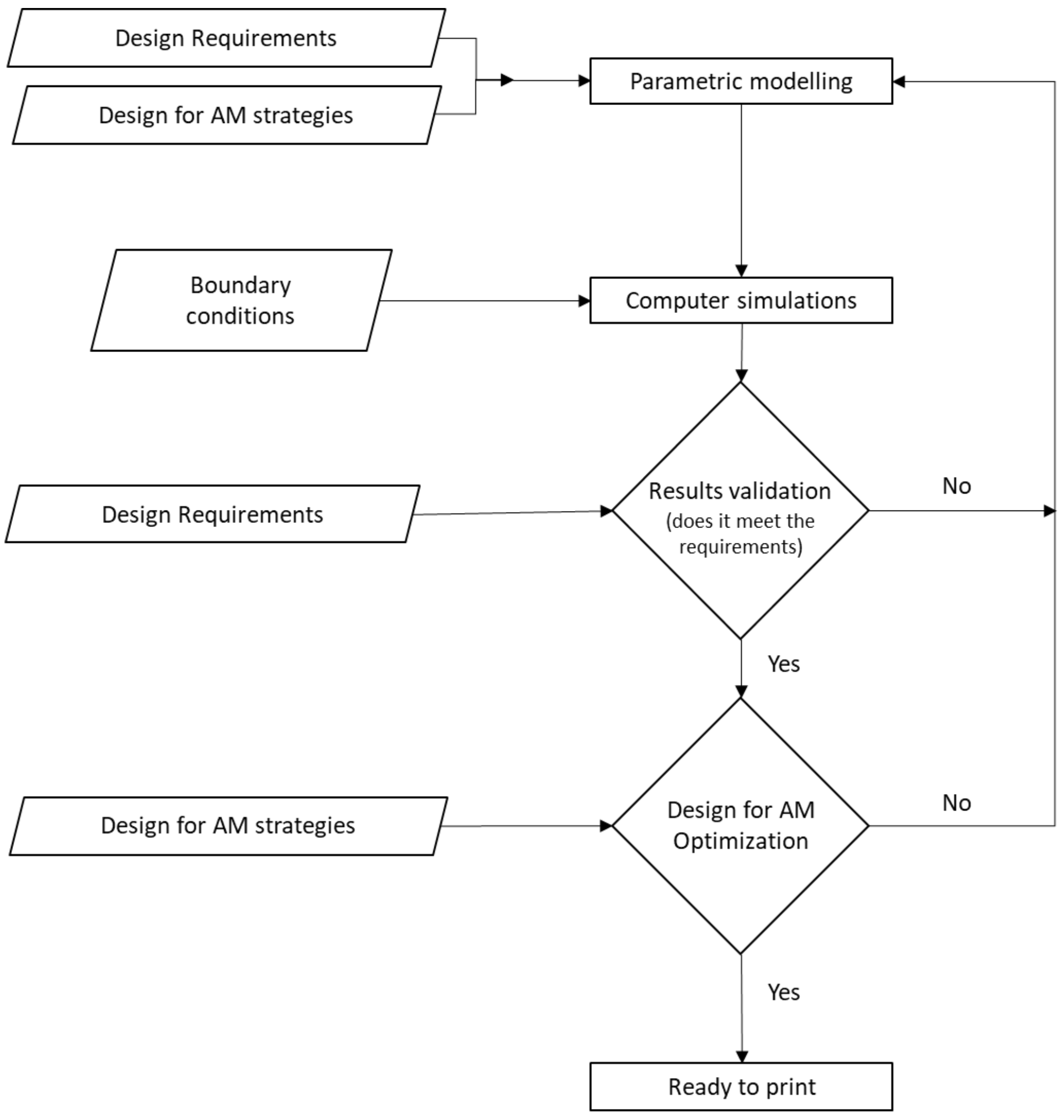


Figure 46 Optimal Workflow for Designing for AM

2. What are the challenges faced by the designers while designing for Additive Manufacturing in terms of the current software capabilities?

The software chosen for answering the research questions are very powerful. Their capabilities are exceptional when compared to other commercially available software in the market. However, to gain the complete benefit of the AM the design software must include features that can give feedback on the design concerning design principles of the AM. Due to the lack of such features in the software, the designing task enters multiple loops of design and validation for DfAM. Therefore, reducing the productivity and efficiency of the design engineers. Furthermore, from this study, it was observed that the software behaves with lag and slow response as the complexity of the geometries and file size of the design increases. This discourages the designers to try the complex lattice structures in their designs. Therefore, reducing the intuition of the design engineers to work around with the principles of AM and instead force them to use standard and simple designs. In addition to this, there are only a few softwares that provide easy exchange of CAD data. This issue increases the complexity of workflow for using the CAD files from one software to another. Hence considering the software, which is capable of generating Lattice structures parametrically, it would be good to have a feature that can export the generated geometries into neutral CAD file formats

3. Can lattice structures with complex geometries be designed by conventional CAD software?

The answer is yes. The software used to answer this question is Siemens NX which has the capability to create cellular/lattice structures. However, a faster generation of lattice requires considerably high-end computer hardware in terms of processing power, graphics, and RAM. For lower tessellation factor (which creates a better surface of the lattice), the lattice generation takes more time depending upon the number of lattices and complexity.

On the other hand, the nTop Platform, which is a software designed for implicit modeling and lattice creation, is very efficient in creating the lattice structures with the faster generation of lattice structures as compared to Siemens NX and it can also generate minimal surfaces with faster speed. The major disadvantage of both the software is they cannot export the lattice structure files into a solid file format.

4. Can lattice structures be simulated for thermal load behavior using computational software?

The software used to answer the question is Ansys AIM. Yes, the computational software allows simulation of lattice structures. Having said that, the time for setting up the simulation and running the calculation increases with the increase of the complexity of the geometry. Therefore, methods like topology optimization would be a better option to create lattice structures or organic structures for AM parts. In addition to this, for simulating complex lattice structures, integrating the nTop Platform or similar software into the workflow can improve the meshing efficiency. nTop Platform (version 2.4.5), has features to create the nodes for boundary conditions and export them to most well established simulation software. Hence, this makes it easier to apply boundary conditions for complicated triangulated surfaces.

5.2 Discussion

Additive Manufacturing is gaining importance in both the product development stage and the product manufacturing stage. The manufacturing constraints raised by subtractive and formative methods in terms of manufacturing complex structures are lifted by AM. These structures which facilitate lightweight, high performance, and high strength to weight ratio can be manufactured and used in a wide range of engineering applications. The DfAM increases efficiency and reduces uncertainties in both the designing stage and manufacturing stage of AM with the help of its principles, rules, and guidelines. However, the new challenge lies in designing these structures according to the requirement such as matching the mechanical or thermal load, weight, and strength requirements. For design engineers who have worked on designing components for conventional manufacturing, the task of designing for AM becomes demanding. Therefore, most CAD software has considered adding features related to AM such as Lattice structures, Support generations, and Topology Optimization. Training and creating awareness about the available software, their workflow, and best practices in implementing DfAM improves the designer's productivity and efficiency.

For the mechanical designers and the design managers who are planning to make use of AM Technology, the following recommendations may be beneficial.

1. Engineering Design- CAD

From the study, it can be noted that the software-based parametric generation of lattice structures and minimal surfaces is easier. In contrast, the manual creation/modeling of these surfaces is time-consuming and inefficient. Depending upon the activity in the downstream, the choice of method for creating these structures should be chosen.

2. Engineering Design- CAE

From the investigation made through this study, it can be concluded that for computer simulations, the best choice of the input format is a solid file (STEP or IGES). Hence, the recommended approach is using a parametric design that allows exporting the files into solid file formats. Solid file formats are easy to set up and simulate, compared to surface file formats like STL. Nevertheless, software like the nTop Platform allows the generation of lattice structures and also allows simulations. As of April 23, 2020, the version 2.4.5 supports mechanical analysis like linear static, modal, and buckling structural and steady-state thermal analysis.

3. DFSS methodology for DFAM

It can be noted from the study, that the integration of Design for Six Sigma methodology streamlines the design flow. During the design process for AM, there are several parameters that are intrinsic to AM. DFSS tools such as AHP and Pugh's concept selection matrix as shown in the case study can play a major role in data-driven decision- making. Therefore, to reduce the complications and uncertainty, integration of DFSS is recommended.

5.3 Scope for Future work

For future works, the research can be extended with a detailed study on developing a workflow for specific methods of DfAM such as Part Consolidation, Topology optimization, Lattice structures, and Multi-Material design. The study can be further narrowed down by choosing a software platform and understanding the workflow and developing best practices. The research output can be presented as a database of guidelines and workflow which will be a support for the mechanical designer to design for Additive Manufacturing.

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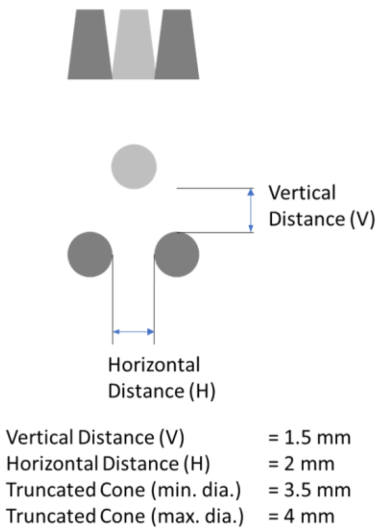
Appendices

Appendix 1. Thermal Analysis results

The results from the Conjugate heat transfer analysis are tabulated in the following tables according to the Pin Placement Strategies used.

1. Type A - Pin Placement Strategy A

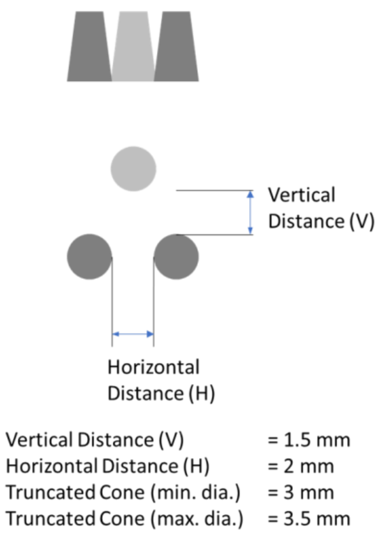
Type A Pin Placement Strategy A



	Inlet Pressure Maximum (bar)	Inlet Pressure Minimum (bar)	Inlet Temp (C)	Temp near heat zone(C)
Case A_1	82	80	500	936
Case A_2	82	80	400	865
Case A_3	82	80	300	796
Case A_4	81	80	500	1070
Case A_5	81	80	400	920
Case A_6	81	80	300	850

2. Type B - Pin Placement Strategy B

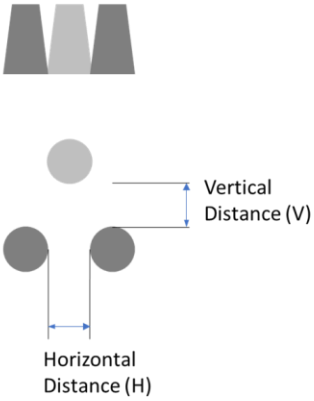
Type A Pin Placement Strategy B



	Inlet Pressure Maximum (bar)	Inlet Pressure Minimum (bar)	Inlet Temp (C)	Temp near heat zone(C)
Case B_1	82	80	500	923
Case B_2	82	80	400	862
Case B_3	82	80	300	733
Case B_4	81	80	500	1010
Case B_5	81	80	400	903
Case B_6	81	80	300	859

3. Type C - Pin Placement Strategy C

Type A Pin Placement Strategy C

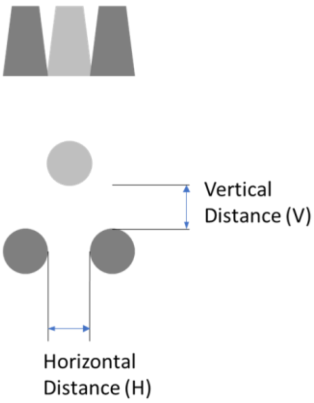


Vertical Distance (V) = 1.5 mm
Horizontal Distance (H) = 2 mm
Truncated Cone (min. dia.) = 2.5 mm
Truncated Cone (max. dia.) = 3 mm

	Inlet Pressure Maximum (bar)	Inlet Pressure Minimum (bar)	Inlet Temp (C)	Temp near heat zone(C)
Case C_1	82	80	500	871
Case C_2	82	80	400	825
Case C_3	82	80	300	695
Case C_4	81	80	500	982
Case C_5	81	80	400	870
Case C_6	81	80	300	805

4. Type D - Pin Placement Strategy D

Type A Pin Placement Strategy D

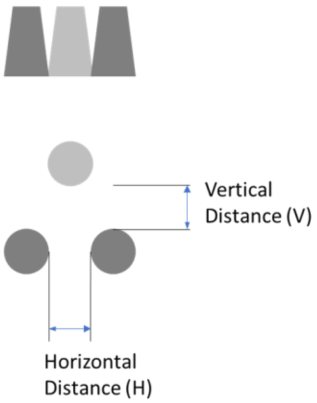


Vertical Distance (V) = 1.5 mm
Horizontal Distance (H) = 2 mm
Truncated Cone (min. dia.) = 2 mm
Truncated Cone (max. dia.) = 2.5 mm

	Inlet Pressure Maximum (bar)	Inlet Pressure Minimum (bar)	Inlet Temp (C)	Temp near heat zone(C)
Case D_1	82	80	500	850
Case D_2	82	80	400	815
Case D_3	82	80	300	620
Case D_4	81	80	500	906
Case D_5	81	80	400	825
Case D_6	81	80	300	760

5. Type E - Pin Placement Strategy E

Type A Pin Placement Strategy E

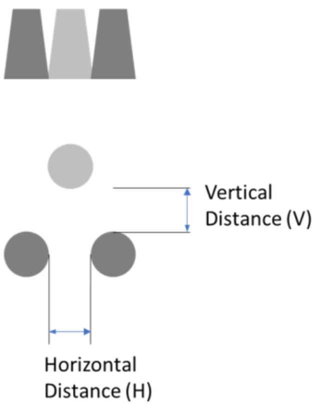


Vertical Distance (V) = 1.5 mm
Horizontal Distance (H) = 2 mm
Truncated Cone (min. dia.) = 1.5 mm
Truncated Cone (max. dia.) = 2 mm

	Inlet Pressure Maximum (bar)	Inlet Pressure Minimum (bar)	Inlet Temp (C)	Temp near heat zone(C)
Case E_1	82	80	500	780
Case E_2	82	80	400	694
Case E_3	82	80	300	586
Case E_4	81	80	500	829
Case E_5	81	80	400	736
Case E_6	81	80	300	652

6. Type F - Pin Placement Strategy F

Type A Pin Placement Strategy F



Vertical Distance (V) = 1.5 mm
Horizontal Distance (H) = 2 mm
Truncated Cone (min. dia.) = 1 mm
Truncated Cone (max. dia.) = 1.5 mm

	Inlet Pressure Maximum (bar)	Inlet Pressure Minimum (bar)	Inlet Temp (C)	Temp near heat zone(C)
Case F_1	82	80	500	765
Case F_2	82	80	400	669
Case F_3	82	80	300	563
Case F_4	81	80	500	812
Case F_5	81	80	400	706
Case F_6	81	80	300	627

Appendix 2. MATLAB Code for Gyroid

```
clear all
close all
clc

x_period = 4;
y_period = 4;
z_period = 4;

[x,y,z] = meshgrid(0:0.1:x_period*3.14159265359, 0:0.1:y_pe-
riod*3.14159265359, 0:0.1:z_period*3.14159265359);
f = cos(x).*sin(y) + cos(y).*sin(z) + cos(z).*sin(x);

figure(1)
isosurface(x,y,z,f)
axis equal
xlabel('X')
ylabel('Y')
zlabel('Z')

hold on

figure(2)
isosurface(x,y,z,f)
axis equal
xlabel('X')
ylabel('Y')
zlabel('Z')
view(2)
figure(3)
isosurface(x,y,z,f)
axis equal
xlabel('X')
ylabel('Y')
zlabel('Z')
view(-45,36)

fv = isosurface(x,y,z,f)

stlwrite('0_to_pi_gyroid.stl',fv)
```