Design of flexible lattice structures

a design for additive manufacturing perspective

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Design of flexible lattice structures - A design for additive manufacturing perspective

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A design for additive manufacturing perspective

Satabdee Dash

LICENTIATE THESIS

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Abstract: Recent years has seen an unprecedented growth in emerging technologies like Additive manufacturing (AM), augmenting the manufacturing capabilities through a multitude of opportunities while also introducing unique constraints, such as support structures, and post-processing requirements. Taking full advantage of the potential of AM demands product designs to be optimised for both opportunities and constraints specific to AM, requiring evolution from the traditional design for manufacturing to design for additive manufacturing (DfAM). Although majority of studies related to product design within DfAM focus specifically on stiffness maximisation, the domain of flexibility remains under-explored. One of the ways to explore the domain of flexibility, is through flexible structures which are often seen in the applications that require structural flexibility, such as in robotics for locomotion, foot orthotics in health care applications, cranial helmets in shock absorber applications, among others. Among the range of flexible structures that make it possible to achieve flexibility in such applications, lattice structures have been frequently researched due to the design freedom offered by their structural arrangement, relative ease of computation, and tunability of desirable mechanical properties. Although these structures have been investigated to harness the structural flexibility that they offer, a significant gap in research has been observed when focusing on the interplay between the design of flexible lattice structures and DfAM. Addressing this gap, the objective of the presented research is to advance the state-of-the-art in DfAM by enhancing knowledge on how to design flexible lattice structures specifically tailored for AM.

To fulfill the research objective, this research follows the design research methodology (DRM), and involves three studies combining both quantitative and qualitative data collection and analysis methods. The first study is a broader study involving a systematic literature review in DfAM, and the subsequent studies are empirical studies involving laboratory and computation-based experiments with a narrow focus on the design of flexible lattice structures within the context of DfAM.

The systematic literature review revealed that when DfAM is concerned, different design strategies are available for general lattice structures and its variants such as functionally graded lattice structures, conformal lattice structures, multi-material lattice structures, mostly supporting in geometric modelling and finite element-based design evaluation. Other available design strategies enable design optimisation specifically focusing on gradient based TO and multi-scale structural optimisation, address design implications such as cost reduction, and enable incorporation of design parameters and AM specific constraints. However, there is a scarcity of design strategies enabling manufacturing analysis-based design evaluation and other forms of design optimisation (e.g., size and parametric optimisation), with none addressing design rules and guidelines for lattice structures. Thus, the outcomes of the first study provide insights into the existing design strategies, and potential gaps, assisting in their adaptation or extension into the narrower field of flexible lattice structures.

The second and third studies combinedly revealed factors influencing the design of flexible lattice structures, and their effect on structural performance, i.e., compressive behaviour - an indicator of flexibility. The second study revealed that printing orientation is a crucial design parameter showing its substantial impact on deformation behaviour and material failure of lattice structures with no notable effect on plastic deformation that relies more on lattice structure topology - another important design parameter. The third study revealed that manufacturing deviations in as-printed parts is a crucial manufacturing constraint, especially for thin strut-based structures typically seen in lattice structures for light-weighting applications. This study revealed the deviations in geometry (tapered strut geometry with elliptical cross-section compared to their geometrical model), and material of as-printed parts and demonstrated their impact on the compressive behaviour of printed parts. The third study also proposed a finite element based numerical model to incorporate these deviations enhancing the prediction accuracy of the compressive behaviour, thus, assisting in the design of flexible structures.

The presented research has both academic and industrial contribution. Theoretically, it contributes to knowledge within the field of DfAM by providing improved understanding of the influencing factors, and their effect on structural performance when designing flexible lattice structures within the context of DfAM. Industrially, it offers invaluable insights that can aid engineering designers and practitioners in creating flexible lattice structures for various applications, such as upholstery design in furnitures, foot orthotics for patients, among others. For instance, the presented research provides insights related to geometrical and numerical modeling, design tolerances, and numerical simulation based structural analyses specific to flexible lattice structures tailored for AM.

Although this thesis has explored the domain of DfAM to broaden its scope by venturing into the design of flexible lattice structures, future work is needed to design these structures for practical industrial use, making it essential for the future research to focus on developing a simulation driven design approach using the insights produced in this thesis, while also venturing into advanced numerical modelling, advanced lattice designs, and performing scale-up studies within industries.

Key words: Design for additive manufacturing, DfAM, lattice structures, flexibility, compuational methods, numerical modelling, engineering design process

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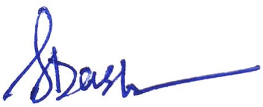
Signature  Date 2024-02-01

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"For an idea that does not first seem insane, there is no hope."

(Albert Einstein)

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Abstract

Recent years has seen an unprecedented growth in emerging technologies like Additive manufacturing (AM), augmenting the manufacturing capabilities through a multitude of opportunities while also introducing unique constraints, such as support structures, and post-processing requirements. Taking full advantage of the potential of AM demands product designs to be optimised for both opportunities and constraints specific to AM, requiring evolution from the traditional *design for manufacturing* to *design for additive manufacturing (DfAM)*. Although majority of studies related to product design within DfAM focus specifically on stiffness maximisation, the domain of flexibility remains under-explored. One of the ways to explore the domain of flexibility, is through flexible structures which are often seen in the applications that require structural flexibility, such as in robotics for locomotion, foot orthotics in health care applications, cranial helmets in shock absorber applications, among others. Among the range of flexible structures that make it possible to achieve flexibility in such applications, lattice structures have been frequently researched due to the design freedom offered by their structural arrangement, relative ease of computation, and tunability of desirable mechanical properties. Although these structures have been investigated to harness the structural flexibility that they offer, a significant gap in research has been observed when focusing on the interplay between the design of flexible lattice structures and DfAM. Addressing this gap, the objective of the presented research is to advance the state-of-the-art in DfAM by enhancing knowledge on how to design flexible lattice structures specifically tailored for AM.

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Academically, the presented research contributes to DfAM research by providing improved understanding of the influencing factors, and their effect on structural performance when designing flexible lattice structures tailored for AM. Industrially, it offers valuable insights for aiding engineering designers and practitioners, such as insights related to geometrical and numerical modeling, design tolerances, and numerical simulation based structural analyses specific to flexible lattice structures tailored for AM. Although this thesis has explored the domain of DfAM to broaden its range of applications through flexible lattice structures, future work remains to realise such structures for practical industrial use.

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I would like to express my deepest gratitude to my supervisors, Glenn Johansson and Axel Nordin for their invaluable guidance, support, and insightful feedback throughout the entire process of my research and in writing this thesis. Thanks to your expertise and encouragement that has been instrumental in shaping this work.

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List of appended papers

Paper A

Dash, S., Nordin, A., and Johansson, G. (2023). *Design for additive manufacturing (DfAM) in Engineering Design: A systematic literature review adopting a dual DfAM perspective*, Manuscript submitted to Additive Manufacturing journal.

Author contributions: Satabdee Dash is the lead author, responsible for the research design, data collection, analysis, and synthesis of the study. She has written the first draft of the paper, including visualisations, and referencing, and performed successive revisions using the feedback from Axel Nordin, and Glenn Johansson. Both the second and third authors were actively involved in the literature screening and provided valuable insights regarding data analysis, and presentation. Glenn Johansson provided feedback from an overall methodological perspective, and Axel Nordin provided feedback specific to the technical subject involved, while also supporting in the quantitative analysis for a portion of the results.

Paper B

Dash, S., Nordin, A. (2022). *Effects of print orientation on the design of additively manufactured bio-based flexible lattice structures.* Paper presented at the NordDesign 2022 conference, Copenhagen, Denmark.

Author contributions: Satabdee Dash is the lead author, responsible for the research design, data collection by manually performing all laboratory experiments, and wrote the first draft of the paper including visualisations and referencing. She has performed successive revisions on the paper according to the feedback from Axel Nordin, and conference reviewers. Axel Nordin was actively involved during the data analysis, and provided valuable feedback on the presentation of results, and for improving the paper during final submission to the conference.

Paper C

Dash, S., Nordin, A. (2023). *Towards realistic numerical modelling of thin strut-based 3D-printed structures*. Paper presented at the ICED 2023 conference, Bordeaux, France.

Author contributions: Satabdee Dash is the lead author, responsible for the research design, data collection involving geometrical measurements, and laboratory experiments, and wrote the first draft of the paper including visualisations and referencing. Together with Axel Nordin, Satabdee Dash has performed numerical simulations. The experimental results were analysed by Satabdee Dash, and the numerical results were analysed by Axel Nordin. Both the authors contributed equally to the presentation of results. Satabdee Dash has performed successive revisions on the paper according to the feedback from Axel Nordin, and conference reviewers.

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List of abbreviations

AM	Additive manufacturing
3DP	Three-dimensional printing
DfA	Design for assembly
DfM	Design for manufacturing
DfAM	Design for additive manufacturing
SDD	Simulation driven design
DRM	Design research methodology

1 Introduction

This chapter presents the background, problem statement, and objectives of the research, followed by research questions and research scope.

1.1 Background

Technological innovation plays a pivotal role in achieving sustainable development goals (SDG) and fostering sustainable growth in the manufacturing industry (MIT, 2019). The advent of the fourth industrial revolution, Industry 4.0, has transformed manufacturing by leveraging emerging technologies such as additive manufacturing (AM) to improve manufacturing capabilities, enable decentralised production, reduce waste, and reduce material usage while also reducing the lead time (e.g., in spare part production) and manufacturing costs (e.g., in low volume production) (Kamble et al., 2018; Lu, 2017). Additive manufacturing, otherwise referred to as three-dimensional printing (3DP), first developed in the late 1980s (Vaneker et al., 2020), is defined by the American Society for Testing and Materials (ASTM) and International Organization for Standardization (ISO) as the *"process of joining materials to make parts from three dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies"* (ISO/ASTM, 2021). The ability of AM to create sophisticated products with advanced attributes such as novel materials, complex geometries, hierarchical structures, and functional assemblies (Gibson et al., 2015) has resulted in significant advancements in the aerospace, manufacturing, and biomedical industries (Vaneker et al., 2020).

Due to the opportunities offered by AM, it has transformed from rapid prototyping into a production technology (AMFG, 2019; Vaneker et al., 2020). However, in comparison to conventional mass production technologies, AM exhibits inferior performance with regard to manufacturing speed, accuracy, repeatability, and cost (Dilberoglu et al., 2017). Aside from that, AM has its own set of constraints, such as support structure requirements and post-processing requirements, making it important for the product designs to be optimised both for the opportunities and constraints specific to AM (Pradel et al., 2018). This led to the evolution of conventional Design for Manufacturing (DfM) and Design for Assembly (DfA) into *Design for Additive Manufacturing (DfAM)* to fully leverage the unique characteristics associated with AM (Bourell et al., 2009). As mentioned in Laverne et al. (2015), literature concerning DfAM tends to be of three types: a) opportunistic DfAM aimed at harnessing AM opportunities, b) restrictive DfAM aimed at incorporating AM constraints, and c) dual DfAM aimed at harnessing AM opportunities whilst incorporating the associated constraints.

This rapidly growing field of DfAM has witnessed great involvement from the scientific community, as indicated by the significant growth in research publications during the past decades. Over the past decade, several researchers have investigated different aspects of DfAM, contributing to the advancement of this research field (Alfaify et al., 2020; Lopez Taborda et al., 2021; Obi et al., 2022; Pradel et al., 2018). While the majority of the studies in this domain have primarily concentrated on product design with the objective of maximising stiffness while simultaneously reducing weight (e.g., Dalpadulo et al., 2020; Diegel et al., 2020; Galati et al., 2020; McEwen et al., 2018), the domain of flexibility, i.e., maximising compliance within DfAM, remains relatively under-explored. One of the ways to explore the domain of flexibility is through flexible structures. In general, flexible structures are designed for various purposes, such as functional consolidation, weight reduction, and shape transformation. These purposes align with the key motivations for adopting DfAM, such as consolidating parts, generating lightweight structures, and creating complex geometries. Moreover, the domain of flexible structures can broaden the applicability of AM. Despite the shared purposes, there has been limited attention in the literature, with only a few studies exploring the interplay between the design of flexible structures and DfAM (e.g., Air & Wodehouse, 2023; Danun et al., 2021; Park & Park, 2020), thus underscoring an area of research that is still in its infancy and needs further investigation.

1.2 Problem statement

Applications areas that demand structural flexibility involve robotics (e.g., locomotion systems), health care (e.g., foot orthotics), aerospace applications (e.g., aircraft propellers, panels), shock absorber applications (e.g., cranial helmets), etc. The advent of flexible structures, such as adaptive structures (Miura, 1992), deployable structures (Hanaor & Levy, 2001), and compliant structures (Howell, 2013), has made it possible to achieve flexibility in the aforementioned application areas. Compliant structures, which employ flexible structural elements instead of movable joints to consolidate functions into fewer parts and minimise wear, represent one of the most commonly utilised structures when flexibility is desired (Howell, 2013; Pecora et al., 2018). Other ways to harness flexibility include metamaterials, which are structures engineered to behave as materials capable of exhibiting a specific set of effective properties as compared to their base material (Bertoldi et al., 2017; Scheffler & Colombo, 2005), e.g., origami- (Miura, 1992) and kirigami- (Cho et al., 2014) based metamaterials. Among the category of metamaterials known for their tunable mechanical properties, lattice structures stand out as frequently researched structures due to the design freedom offered by their structural arrangement, the relative ease of computation, the ease of tunability of mechanical properties, and other advantages further elaborated in Section 1.4. When flexibility is concerned, there is a plethora of literature on the design of lattice structures, for instance, the design of multi-material compliant lattice-structured beams (Stanković et al., 2015), functionally graded structures inducing flexibility due to metamaterial design (Martínez et al., 2019), and the design of shape-morphing geometric lattices (Boley et al., 2019).

Rapid advancements in AM technologies have facilitated the creation of lattice structures with complex and customised geometries with controllable mechanical properties. Nevertheless, similar to any other manufacturing technology, the extent to which the desired mechanical properties can be attained is limited by the manufacturing constraints in AM. The concept of DfAM promotes the integrated practice of designing parts while considering their manufacturing using AM (Thompson et al., 2016), utilising the full potential of AM (Laverne et al., 2015), which aligns well with the concept of dual DfAM mentioned in Section 1.1. Thus, DfAM in this thesis refers to dual DfAM, unless otherwise stated. Embracing a DfAM perspective facilitates better adoption of AM by designers and engineers (Sossou et al., 2022) and enhances the manufacturability of designs (Rosnitschek et al., 2021) (e.g., enabling complex features with manufacturable geometries). Moreover, it also promotes design innovation, as indicated by Laverne et al. (2015). Hence, adopting DfAM becomes essential when designing flexible lattice structures. However, in the existing literature, there is a scarcity of studies that encompass both DfAM and the design of flexible structures, with studies either utilizing AM solely as a manufacturing technology (Joyee & Pan, 2019; Nelson et al., 2015) or focusing on the redesign of additively manufactured flexible structures for enhancement of flexibility (Merriam, 2016).

Within research addressing lattice structures, flexibility has been investigated in terms of compressive behaviour in a number of studies (Obadimu & Kourousis, 2021; Tancogne-Dejean et al., 2016; Xiao et al., 2015). However, only a few studies address the concept of DfAM (e.g., Air & Wodehouse, 2023; Danun et al., 2021; Park & Park, 2020). To elaborate further, there is a lack of research focusing on the design of flexible lattice structures by simultaneously considering the AM-specific design parameters (e.g., printing orientation) and manufacturing constraints (e.g., support structure requirements) that tend to influence the mechanical behaviour, such as flexibility. Additionally, the current research efforts have mostly involved powder bed fusion (PBF)-based metallic lattice structures and material extrusion (ME)-based polymer structures, indicating the need to explore other AM processes and materials (Obadimu & Kourousis, 2021).

Due to the aforementioned lack of research aimed at designing flexible lattice structures by adopting the concept of dual DfAM, further investigation is necessary, as illustrated in Figure 1.1. The blue lines in Figure 1.1 represent the problem statement, and the yellow (solid and dotted) lines represent the research gap discussed previously in this section. Addressing this research gap is essential as it offers the opportunity to gain insights into designing flexible lattice structures to take advantage of the possibilities of AM, such as individualization or tunable mechanical properties, while taking into account the constraints of AM to ensure manufacturable and cost-efficient designs.

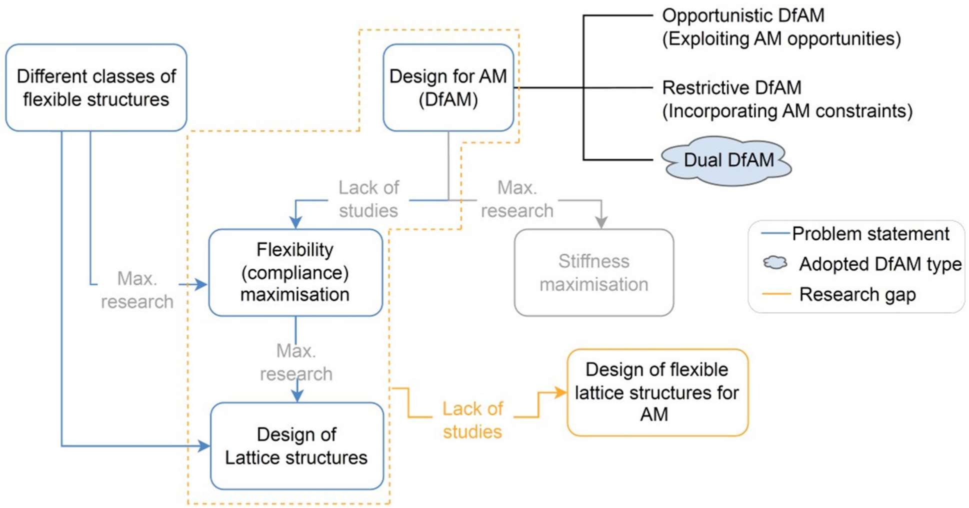


Figure 1.1: Illustration of the problem statement (research gap)

1.3 Objective and research questions

DfAM is a widespread research topic with a focus on design, materials, processes, manufacturing parameters, post-processing, and so on. However, in this thesis, the presented research focuses only on the part design within an engineering design process. Herein, part design refers to any changes in the form or geometry of the part without focusing on the process, machine, or material specific to AM.

To bridge the research gap identified in Section 1.2, the research objective presented in this thesis is *to advance the state of the art in DfAM by enhancing knowledge on how to design flexible lattice structures specifically for AM*.

Four research questions (RQs) have been derived from the objective, as explained below.

The first research question was formulated to be broad enough to explore the current state of DfAM literature. First of all, it is necessary to investigate the existing design strategies[1] that are currently adopted for employing DfAM. This requires clarifying whether there are already some design strategies that can be adapted or extended for fulfilling the objective of this thesis, knowing their type, and how they fit within the context of DfAM. Since the primary focus of the presented research objective involves lattice structures, it requires clarifying the interconnections between these structures and the existing strategies, i.e., how are the design strategies currently employed in the design of lattice structures. It also requires insights into the type of lattice structures, the scope and extent of the contribution of these strategies towards the design of such structures, and any potential gaps that might be observed by understanding these interconnections. These issues were used to formulate the first research question, i.e., **RQ1: How do the existing design strategies within DfAM contribute to the design of lattice structures?**

The second and following research questions narrow down the research focus to DfAM for flexible lattice structures. As mentioned previously, the concept of dual DfAM involves part design by exploiting AM opportunities while incorporating the associated constraints. This requires identifying the factors that can influence the design, i.e., identifying design parameters or the geometry-specific parameters that affect the part design, and the manufacturing constraints that constrain the design. Since flexibility is an important objective in the design of these lattice structures, it requires identifying which of these design parameters and manufacturing constraints can affect structural flexibility. These issues are formulated together into the second research question, i.e., **RQ2: What influencing factors may be considered when designing flexible lattice structures for AM?**

Apart from identifying the aforementioned influencing factors, it is crucial to comprehend the interaction effects of these factors. i.e., how the individual or combination of factors influence the intended part performance, for instance, if there are any obvious structural failures, etc., and clarifying the impact these interactions have on the flexibility of the intended lattice structures. Without such clarifications, it will be difficult to regulate the flexibility of these structures. To understand these issues, the third research question was formulated, i.e., **RQ3: How do the interactions among the influencing factors affect the performance of such structures?**

Identifying the influencing factors and understanding their interaction(s) effects can provide insights into the factors to be considered when designing flexible lattice

[1] In this thesis, the term 'design strategies' is used to collectively represent design methodologies, tools, and methods.

structures. However, it is required to incorporate these factors and corresponding interaction effects, e.g., using computational approaches such as the simulation-driven design (SDD) approach. These computational approaches have been commonly utilised in engineering design processes; hence, much work has been done in such a context, however, their utilisation in complex design problems, for instance, concerning flexible lattice structures, is under-explored. Additionally, for faster design iterations, there might be a need for efficient integration of the intended factors and their interaction effects as well. These issues are formulated into the fourth research question, i.e., **RQ4: How can the influencing factors be incorporated while designing flexible lattice structures for AM?**

1.4 Research focus and delimitations

The presented research lies at the intersection of engineering design, DfAM, and lattice structures, as illustrated in Figure 1.2. Within the domain of engineering design, the engineering design process was emphasised, specifically focusing on the conceptual, embodiment, and detail design phases; within Design for AM, only dual DfAM concepts were adopted for part design within the three aforementioned design phases of an engineering design process, without focusing on DfAM for materials and processes; and within lattice structures, uniform lattice structures were explored ─ all aiming towards generating flexible lattice structures.

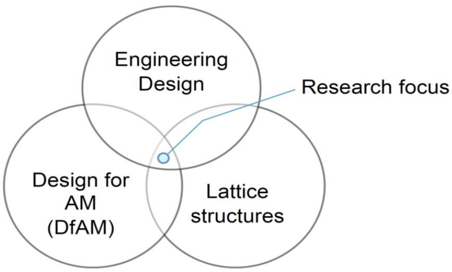


Figure 1.2: Illustration of the research focus

Reiterating from Section 1.3, the current research adopts dual DfAM while focusing only on the part design aspects of DfAM. Among the several AM processes available, this research focuses only on the polymer PBF process, more specifically selective laser sintering (SLS). The process selection was inspired by the availability of in-house printers and compatibility with the chosen material.

The chosen material is a bio-based polymer, PA1101, selected due to the biopolymer focus within a research project named STEPS (STEPS) that has enabled a portion of this research. Although there are various bio-based materials available commercially, those that are available for 3DP at a reasonable cost are limited. Additionally, since there are scalability issues associated with in-house-produced bio-based 3DP-compatible materials produced by STEPS project partners at the department of Chemical Engineering at LTH, the chosen material, PA 1101, tends to be the current suitable option. The adopted printer process settings and machine operator were fixed based on the availability of printer options that were rendered suitable to produce good-quality samples for experimental investigations.

Lattice structures were selected as the starting point for investigating potential synergies between flexible structures and DfAM, given their high strength-to-weight ratio and structural simplicity compared to other types of cellular structures. More specifically, uniform-density lattice structures with linear struts have been the current subject of investigation. Due to the preliminary nature of experimentation, it was chosen to begin with simple lattice topologies available in the existing literature. Also, as compared to non-linear plate or sheet-based lattice structures, linear strut-based structures enable easier and faster integration with commercially available computational and geometrical modeling tools. The presented research has been limited to only thin struts (maximum 0.8 mm diameter), owing to the fact that thinner struts contribute towards our objective of attaining structural flexibility.

The application area in focus within the STEPS project is the furniture industry, more specifically a Swedish furniture company (JI) that has shown interest in investigating flexible lattice structures for upholstery design. However, the research approach presented in this thesis has not been restricted by the cases within this application area. Rather, the upholstery application in the STEPS project has served as a motivation for this research.

1.5 Thesis outline

This report is divided into five chapters.

Chapter 1 introduces the topic, problem statement, research objectives, and related delimitations.

Chapter 2 describes the theoretical foundation that underpins this proposition.

Chapter 3 describes the research methods used to conduct the intended research.

Chapter 4 summarises the results in terms of the appended papers.

Chapter 5 presents and discusses the research conclusions along with research contributions and suggestions for future work.

2 Theoretical foundation

This chapter outlines the theoretical foundation that the research presented in this thesis is based on. An overview of the key concepts related to this research is discussed along with some insights on the related existing literature.

2.1 Additive Manufacturing

In recent years, due to technological advancements, manufacturing processes have become more digital, flexible, and efficient (Lu, 2017). Additive manufacturing, or 3DP, is a transformative technology that additively creates 3D objects by depositing material layer by layer from a digital 3D model, as opposed to conventional subtractive processes such as turning, milling, shaping, and so on. A wide variety of materials, including metals, ceramics, polymers, composites, and hybrids, can be fabricated with AM. The general process of AM is illustrated in Figure 2.1. In this process, the object data is captured from computer-aided design (CAD) models or by using 3D scanners. This data is converted into 3D models, usually in standard tessellation language (STL) or additive manufacturing file format (AMF), which are sliced into layers and fed into the printers. The printers perform the printing operation by layer-wise material addition. Upon repetitive deposition of material on the preceding layer, a 3D object is produced (Gibson et al., 2015).

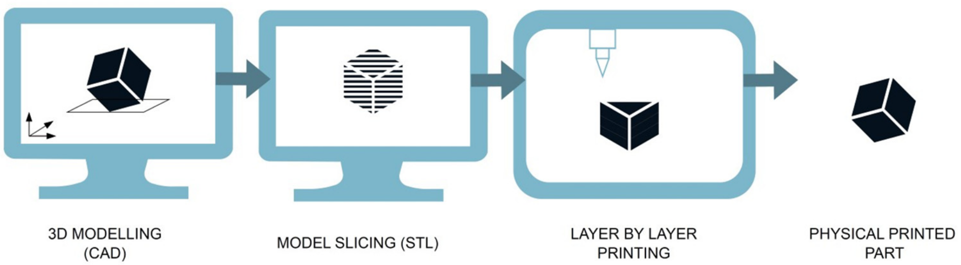


Figure 2.1: A general additive manufacturing process

The American Society for Testing and Materials (ISO/ASTM, 2021) has categorised AM into powder bed fusion (PBF), material extrusion (ME), binder jetting (BJ), material jetting (MJ), VAT photopolymerization (VATP), directed energy deposition (DED), and sheet lamination (SL). The PBF technology includes laser PBF (L-PBF), suitable for polymers and metals. The L-PBF process for polymers is commercialised as selective laser sintering (SLS), wherein laser is used to fuse polymer particles in a localised manner. The process involves lowering the powder bed containing material powder, applying a new layer, and exposing it with the laser to create a layer bond. This iterative process results in a 3D polymer part wherein the surrounding powder acts as temporary support material, which is removed later (Kummert et al., 2021). The SLS process has been illustrated in Figure 2.2.

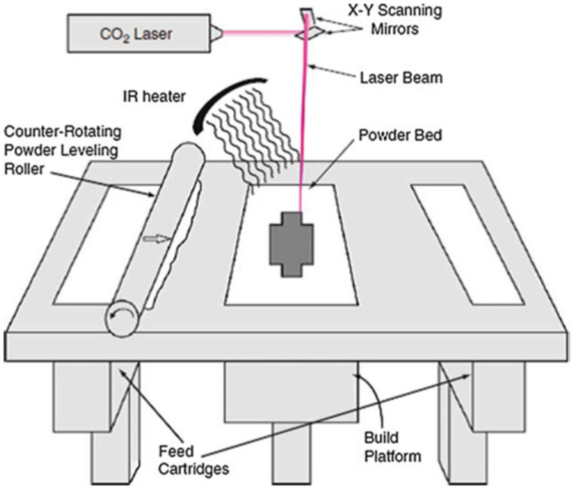


Figure 2.2: Illustration of the SLS process. Courtesy: Gibson et al. (2015)

Additive manufacturing offers unique capabilities such as shape complexity (i.e., possibility to build virtually any shape), hierarchical complexity (i.e., possibility to design and fabricate multi-scale structures), material complexity (i.e., possibility to process material one point or one layer at a time), and functional complexity (i.e., possibility to fabricate fully functional assemblies or mechanisms) (Gibson et al., 2015). Nevertheless, similar to any other manufacturing technology, AM has its own set of constraints. According to Deloitte (2019), these constraints include technical constraints (e.g., lack of improved material properties, incomplete global quality standards, lack of re-defined supply chain (SC) for AM), design constraints (e.g., difficulty in exploiting the design freedom, support structure requirement, shape distortion due to heat accumulation, generation of residual stresses, post-processing requirements), capability constraints (e.g., lack of skilled workforce, lack of standardised design guidelines, lack of advanced process simulation software), and financial constraints (e.g., difficulty in creating a positive business case for serial production, lack of cost models, difficulty in analysing overall impact of AM on existing SC). Although several of these constraints have not been addressed completely, there has been ongoing research attempting to eradicate them (Kalyan et al., 2021; Pérez et al., 2020).

To harness the design potential of AM, it is necessary to identify parts in a product where the benefits of AM create the most value to the customers (Klahn et al., 2015). Whether a part can benefit from the previously mentioned AM capabilities can serve as a useful criterion for identifying suitable parts to fully leverage the geometric freedom offered by AM. A detailed explanation of these criteria, along with different examples of their implementation in practical scenarios, is presented in Klahn et al. (2014). Additional factors that influence the suitability of parts for AM include part volume, expected cost, advantage over other manufacturing techniques, compatible materials, mechanical requirements, and desired surface finish (Liu et al., 2020). Therefore, selecting a part for AM is difficult and entails a trade-off between different design and manufacturing parameters (Gibson et al., 2015).

2.2 Engineering Design

A general engineering design process, as proposed by Pahl et al. (2007), involves four main phases, as illustrated in Figure 2.3: planning and task clarification (involves information specification), conceptual design (involves conceptualisation or solution specification), embodiment design (involves layout specification), and detail design (involves production specification).

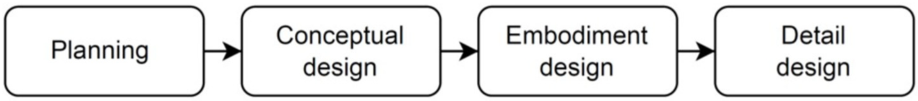


Figure 2.3: Engineering design process proposed by Pahl et al. (2007)

According to Pahl et al. (2007), during the planning phase, information specifications for a product are derived from functional and customer requirements. Since decisions made during the early design phases highly affect the cost and development time of a product, the information specifications from the planning phase are thoroughly investigated during the conceptual design phase, and accordingly, the most promising solution concepts are developed during the embodiment and detail design phases. In this way, engineering design plays a crucial role in shaping the physical attributes of a product to best fulfil customer requirements (Ulrich & Eppinger, 1995). Today, different phases of engineering design have been dominated by computer-aided methods, e.g., CAD for geometric modelling, and computer aided engineering (CAE) commercial software for design evaluation, easing the design process for advanced technologies such as additive manufacturing.

2.3 Design for X

Design for X (DfX) is a generic name for design strategies adopted to improve product design and the design process from a particular perspective, which is represented by 'X' (Kuo et al., 2001). Within DfX, the 'X aspect of interest' is essential to be considered at the early design phases in an engineering design process (Pahl et al., 2007) to highlight important considerations for performing informed design decisions (Tomiyama et al., 2009). Design for X is a subset of design theory and methodology (DTM) that is obtained by focusing on various concrete design goals within design. DTM is about design processes and activities rather than about products. To elaborate further, it can be said that *"Design theory is about how to model and understand design; while design methodology is about how to design"* (Tomiyama et al., 2009, p. 544). A few of the popular DfX strategies include DfA and DfM, subsumed under 'Design for Manufacturing and Assembly' (DfMA) (Kumke et al., 2016).

2.4 Design for additive manufacturing (DfAM)

With the evolution of AM, the design freedom associated with it has been constantly expanding, thereby alleviating some conventional design limitations. For instance, limitations in injection molding such as the requirement of draft angles, minimisation of re-entrant features, and weld lines (Yang & Zhao, 2015), in addition to the difficulties in manufacturing hollow interiors and internal channels, can be overcome by adopting AM (Calzado et al., 2019). Aside from that, AM technologies offer other unique capabilities, as mentioned in Section 2.1. However, to fully leverage these capabilities, it is necessary to rethink DfM (Rosen, 2014), thus enabling the evolution from DfM to DfAM. Owing to the aforementioned benefits, the rapidly growing field of DfAM has witnessed greater involvement of the scientific community, as indicated by the significant growth in research publications during the past decades.

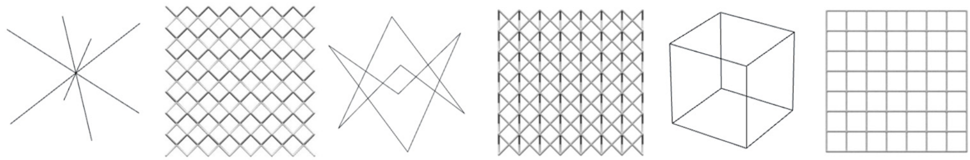
According to Rosen (2007), DfAM is characterised as a *"synthesis of shapes, sizes, geometric mesostructures, and material compositions and microstructures to best utilise manufacturing process capabilities to achieve desired performance"* or to maximise product performance (Gibson et al., 2015). However, despite the attempt at establishing a general definition, DfAM has encountered diverse interpretations within the research community. While some researchers connect DfAM with the exploitation of design potentials or constraints associated with AM, others consider AM processes or material-process relationships as DfAM, and some view it as a set of strategies meant to assist designers in creating designs tailored for AM (Kumke et al., 2016; Obi et al., 2022).

Within the existing engineering design processes, as quoted by Saunders (2018), most of them that employ AM usually 'Adapt for AM' rather than 'Design for AM'. For instance, parts are often designed without keeping AM in mind, resulting in increased sacrificial support structures to ensure buildability. As a result, the manufacturing process is rendered ineffective, costing a significant amount of resources and resulting in low-quality products. This necessitates re-framing the engineering design process in order to maximise the benefits of AM while tackling the challenges that come with it. This, in turn, demands appropriate design strategies that can support DfAM while taking AM constraints into account.

When DfAM is concerned, different design strategies have been implemented in different phases of the engineering design process and are intended for different purposes. Some of them include strategies for generative design, for example, using topology optimisation (Leary et al., 2014), for the design of multi-scale structures, e.g., using lattice structures (Tang et al., 2015), for multi-material design (Stanković et al., 2015), for mass customization (Reeves et al., 2011), for part consolidation (Yang et al., 2015), and other strategies that facilitate AM-enabled features. However, the existing design strategies for supporting DfAM are limited in their scope, i.e., they are tailored to a specific design stage and/or limited to certain types of AM processes (Kumke et al., 2016; Lopez Taborda et al., 2021). Additionally, the existing strategies tend to focus on incremental improvements to existing designs (e.g., improving weight, functionality, etc.) and are almost developed independently instead of building on each other (Lopez Taborda et al., 2021).

2.5 Design of lattice structures

Lattice structures are a subset of cellular structures, comprising connected trusses (i.e., struts) or plates that are either stochastic (e.g., foams, voronoi) or non-stochastic (e.g., lattices) in nature (Gibson & Ashby, 1997), and have proven beneficial for AM due to the design freedom they offer (Ziegler et al., 2017). Lattice structures are hollow structures with an interconnected network of periodically arranged 3D unit cells (Gibson & Ashby, 1997; Seharing et al., 2020), as shown in Figure 2.4. The examples shown in Figure 2.4 consist of struts and nodes, wherein struts link the nodes, and a node serves as a joint where the struts connect (Syam et al., 2018). Other commonly reported strut-based lattice structures have been presented in the review articles by Obadimu and Kourousis (2021) and Savio et al. (2018). Lattice structures have seen widespread applications in biomedical, aerospace, and automotive fields (Obadimu & Kourousis, 2021) due to their unique properties, such as for lightweighting due to their high strength-to-weight ratio characteristics (Obadimu & Kourousis, 2021; Savio et al., 2018; Seharing et al., 2020), for heat exchange due to their high surface area-to-volume ratio (Dong et al., 2017; Savio et al., 2018), and for energy absorption due to their ability to undergo large deformation at a relatively low stress level (Dong et al., 2017; Obadimu & Kourousis, 2021; Savio et al., 2018), among others.



a) b) c)

Figure 2.4: Examples of lattice structures (right) with respective unit cells (left). a) BCC b) FCC c) cubic

Lattice structures are metamaterials, as mentioned in Section 1.2; hence, their micro-architecture can be engineered to exhibit a specific set of effective properties, thus behaving as a monolithic material (Scheffler & Colombo, 2005). Based on the functional requirements, a lattice structure can be designed by taking into account geometry-specific design considerations (Tao & Leu, 2016), such as relative density (i.e., ratio of the density of the lattice structure to the density of the base material it is made of), unit cell size, topology and distribution, and strut thickness, among others (Mahmoud & Elbestawi, 2017). Different types of lattice structures include functionally graded lattice structures (FGLS), where the density of the designed structure is optimally distributed (Nguyen et al., 2021), conformal lattice structures (CLS), where unit cells with different sizes and geometry adapt and conform to the external boundary of the model (Dal Fabbro et al., 2021), and so on. There are different methodologies adopted in existing literature for geometrically modelling these structures, for example, boundary representation (BRep), volume representation (VRep), etc. (Savio et al., 2018); however, the capabilities in commercial CAD software are still limited, with most of them adopting BRep approaches owing to the ease of implementation and incorporation of complexities (e.g., fillets) and reduced computational resources. Some of the available CAD software for geometric modelling of lattice structures includes Rhinoceros 3D, Autodesk Fusion, and nTopology, among others.

2.5.1 Lattice structures as flexible structures

According to Howell (2013), *"if something bends to do what it is meant to do, then it is compliant. If the flexibility that allows it to bend also helps it to accomplish something useful, then it is a compliant mechanism."* Traditionally, designers used stiff or rigid joints for introducing moving functionality (e.g., door hinges or sliding joints). However, as can be seen in moving things in nature, flexibility can also enable such functionalities, generally derived by the bending of flexible parts, for instance, the wings of a bee, the movement of an elephant trunk, etc. (Howell, 2013).

Flexible structures cater to a wide range of applications, owing to the advantages associated with them, e.g., weight reduction (due to the absence of rigid links), reduction of wear and backlash, resulting in durability and increased performance. They provide scope for the integration of functions into fewer parts, potentially reducing cost, assembly, and inventory requirements. Therefore, in order to take full advantage of these structures, continual research into the design and implementation of flexible structures is being conducted, e.g., the design of a flexible skin by introducing a spring and beam arrangement (Li et al., 2009), the design of ultra-stretchable accordion-like structures (Niknam et al., 2020), etc. However, there seems to be a lack of consistency when it comes to the definition of flexible structures that these existing literature focus on. Aside from the previously mentioned benefits, the general class of flexible structures has added advantages, for example, the possibility to achieve multi-state behaviour (for the same application corresponding to different load scenarios, e.g., packaged state versus functional state), multi-functionality (different configurations depending on different functionality requirements), and integrated functionality, among others.

Lattice structures have been previously engineered in a wide variety of applications to serve as flexible structures, e.g., the design of unmanned aerial vehicle wings using periodic lattice structures (Moon et al., 2014) and the design of shape-morphing geometric lattices (Martínez et al., 2019). Another potential application of these flexible lattice structures involves fulfilling the aim of the STEPS project, i.e., replacing foams with 3D printed structures exhibiting foam-like flexibility for upholstery application. Although, this would require utilising bio-based materials to gain the intended sustainable advantage. However, it remains a challenge to mimic the foam-like flexibility using bio-based materials that tend to be stiffer in nature. As mentioned previously, the term ‘flexible structures’ tends to have an inconsistent definition; hence, for the sake of consistency, in this thesis, *‘flexible structures’* are defined as *‘lattice structures that are capable of exhibiting foam-like functionality’*.

2.5.2 DfAM for lattice structures

Advancements in AM technologies have opened doors for the design and fabrication of complex structures with intricate geometries and tailored functional characteristics, e.g., lattice structures (Obadimu & Kourousis, 2021; Savio et al., 2018). During the past few decades, there has been a significant increase in the number of studies investigating lattice structures and their dimensional (Mahmoud

& Elbestawi, 2017) and mechanical properties, both numerically and experimentally (Fleck et al., 2010; Karamooz et al., 2014; Karamooz Ravari & Kadkhodaei, 2014; Obadimu & Kourousis, 2021; Tancogne-Dejean et al., 2016; Wang et al., 2010; Xiao et al., 2015). However, there has been a scarcity of research focusing on the design of lattice structures while simultaneously considering AM-specific design parameters (e.g., printing orientation) and manufacturing constraints (e.g., anisotropy, dimensional inaccuracies), which tend to influence the mechanical behaviour exhibited by the AM parts. Additionally, the current research efforts have mostly involved PBF-based metallic lattice structures and the ME-based polymer structures, indicating the need to explore other AM processes and materials (Obadimu & Kourousis, 2021). Although these structures can be successfully manufactured using different AM processes, it is essential to consider manufacturability, cost, application requirements, and the desired mechanical properties (Tao & Leu, 2016). Some of the key considerations when designing lattice structures for AM (i.e., DfAM of lattice structures) include size (e.g., minimum strut size, unit cell size) and support structure constraints, uncertainties in the morphologies of the printed parts, etc. (Tao & Leu, 2016). The manufacturability of lattice structures with varying topologies, unit cell size, and strut thickness has also been investigated (Kummert et al., 2021). These parameters enable freedom to tune the desired mechanical properties, although the base material properties also influence the mechanical properties (Dong et al., 2017; Mahmoud & Elbestawi, 2017). Different possible combinations of these design characteristics lead to different design options, resulting in different mechanical properties. However, it is difficult to precisely determine these properties just by altering these structural parameters and hence requires experiments, FEA, or homogenisation methods to simulate the impact of topologies on mechanical performance (Dong et al., 2017).

2.6 Simulation-driven design of lattice structures

Simulation-driven design can be defined as "*a design process where decisions related to the behaviour and the performance of the design in all major phases of the process are significantly supported by computer-based product modeling and simulation*" (Sellgren, 1999). Finite element methods (FEM) have been widely adopted to enable simulation-driven design due to their ability to describe the physical state of an object and also simulate its behaviour in a design environment (Sellgren, 1999). For lattice structures, FEM-based numerical modelling has been predominantly used in their design and prediction of mechanical properties (Gautam et al., 2018; Kummert et al., 2021; Tancogne-Dejean et al., 2016), enabling faster prediction by reducing the efforts that would have otherwise required conducting experimental investigations. However, the accuracy of FEM results is often limited by the material model, mesh representation, and geometrical model (Mahmoud & Elbestawi, 2017). Additionally, FEM-based numerical modelling makes it easier to understand the behaviour of lattice structures, e.g., through simulations of stress-strain distributions and failure modes, as reviewed in Obadimu and Kourousis (2021). Some of the most commonly used commercial software include ANSYS (Dal Fabbro et al., 2021) and ABAQUS (Kummert et al., 2021).

When lattice structures are additively manufactured, their as-printed mechanical characteristics often significantly vary (Tkac et al., 2020), requiring complete characterisation. Employing FEM-based numerical modelling alone proves challenging in achieving complete characterisation, necessitating additional experimentation in such cases. While many studies tend to adopt both experimentation and numerical simulations for investigating mechanical properties of lattice structures, e.g., compressive behaviour (Abou-Ali et al., 2020; Alwattar & Mian, 2020; Kummert et al., 2021), they mainly aim for validating the design or the numerical model. Since extensive experimentation for complete characterisation is expensive and time consuming, researchers have been shifting towards using numerical modelling and simulations for a more integrated design process, which is the very essence of simulation-driven design, for example, by incorporating data from experimental characterisation of as-printed lattice structures into numerical models (Gorguluarslan et al., 2015; Tkac et al., 2020; Vrana et al., 2022).

3 Research methodology

This chapter outlines the research methodology adopted in this licentiate thesis. An overview of the research process and research design, including data collection, and data analysis techniques, is presented. The research quality in terms of validity and reliability is also discussed.

3.1 Research process

The research process has been illustrated in Figure 3.1. The problem statement prompting the need for specialised flexible structures designed for AM has been explained in Section 1.2. This led to formulating research gaps, questions, and an initial research plan, all incorporated into a research proposal report presented during the first year. The research centers on the design of flexible structures within the context of DfAM, necessitating a comprehensive grasp of this evolving field. To fulfill this need, a broader Study 1 was conducted within the field of DfAM, resulting in Paper A. Due to the broadness of the study, it was conducted early on and forms the foundation for subsequent empirical investigations in Studies 2 and 3, resulting in Papers B and C, respectively, narrowing down to DfAM for flexible lattice structures. Overall, these studies spanned over three years, addressing all the research questions. This extensive research effort culminated in the presented compilation thesis, which synthesises all the research findings and contributions to the field.

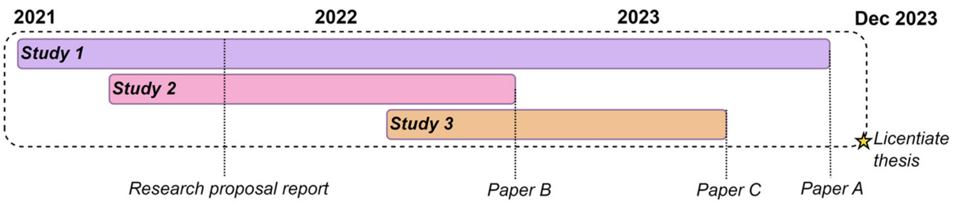


Figure 3.1: Research process - Timeline

The presented research is inspired by the Design Research Methodology (DRM) proposed by Blessing and Chakrabarti (2009), which comprises four iterative stages, i.e., research clarification, descriptive study I, prescriptive study, and descriptive study II. This research followed an adapted version of DRM as illustrated in Figure 3.2, which presents the correlation between the executed DRM stages with the conducted studies, resulting papers, research questions, and the research design for each study. Note that the fourth and final stage is yet to be executed, and hence has not been detailed.

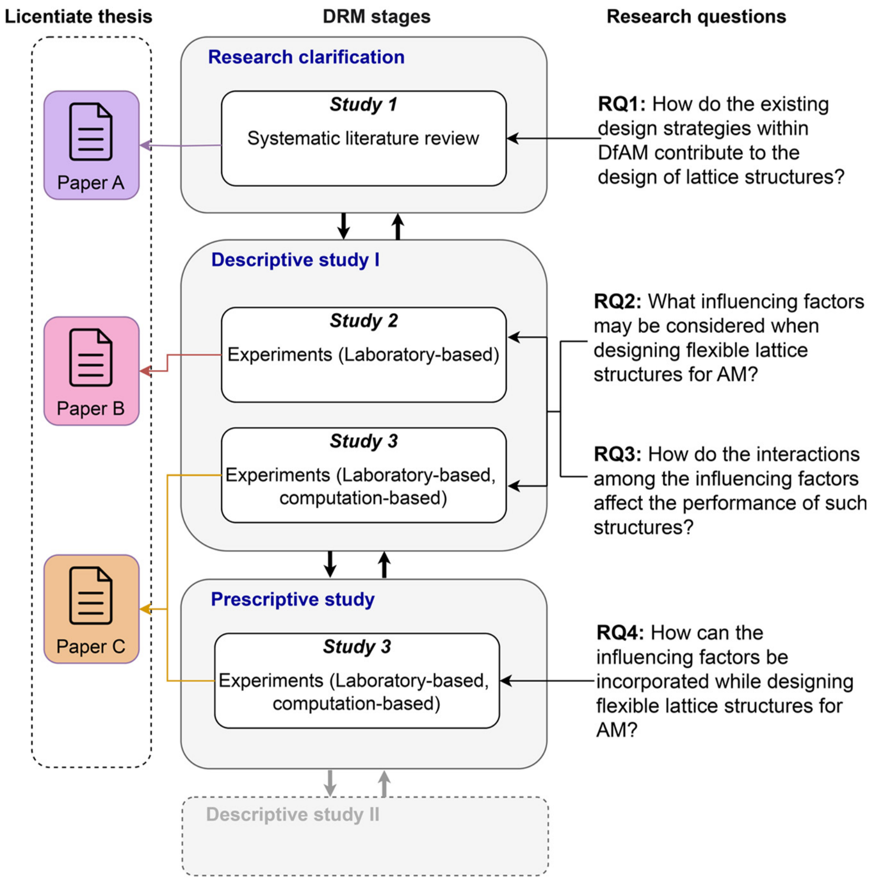


Figure 3.2: Research process - Correlation between DRM stages, conducted studies, resulting papers, research questions, and research design corresponding to each study

Correlation of DRM stages with the research questions

Different stages of DRM within the context of this research have been explained below:

• **Research Clarification (Stage 1):** Involves clarification of the research objective based on the assumptions underpinning the research. In the presented research, a systematic literature review (Study 1) was performed to review the state of the art and the current practices within the field of DfAM.

• **Descriptive Study I (Stage 2):** With a research objective in hand, an in-depth literature review has been performed with a focus on flexible structures designed for AM. However, without sufficient evidence from the literature, two empirical studies (Study 2 and 3) have been performed to get a better understanding of the current state (i.e., the influencing factors and their impact) and lay the foundation for further steps. Upholstery application within the furniture industry has served as a motivation for this research, envisioning upholsteries with foam-like flexibility as a potential application of this research.

• **Prescriptive Study (Stage 3):** In this stage, a design support (e.g., a simulation-driven design strategy) can be created that addresses the factors influencing the current situation and enables transitioning to a desired situation as per the research objective. A step towards this realisation has been facilitated in Study 3, using the findings from Stages 1 and 2. The final stage of DRM (Descriptive study II) involves empirical studies required to assess the applicability and usability of the tools or methods planned to be developed in Stage 3, although the presented research work has not matured enough to reach this stage yet.

3.2 Research design

The presented research follows a combination of both quantitative and qualitative methods. The licentiate studies began with an initial set of qualitative research, using a literature review to gain an understanding of the field of DfAM. As the studies progressed, quantitative research using laboratory-based and computation-based experiments was conducted to get an in-depth understanding of the factors influencing the flexible structures designed for AM. The research design for each of the three studies that are part of this thesis is explained below.

3.2.1 Study 1: Systematic Literature Review

In this research, the first study (Study 1) was conducted to review the overall DfAM research landscape prior to conducting any empirical studies on flexible lattice structures within the context of DfAM. Hence, a systematic literature review was conducted as Study 1, resulting in Paper A. The research methodology adopted for Study 1 follows the procedure by Snyder (2019), whose simplified illustration is presented in Figure 3.3. The study was conducted by examining peer-reviewed journals and review articles from search databases - Scopus (www.scopus.com) and Web of Science (www.webofscience.com) restricted between January 2000 and March 2022 and those that are published in English. The search string was designed to include a specific sequence of words, "Design for additive manufacturing" and its abbreviation "DfAM". The review process is further detailed in Paper A. The literature findings were analysed using content analysis, which is about systematically describing the contents of data by means of coding (Kristina & Gustavsson, 2020). The results of the content analysis were further analysed empirically using quantitative methods. The results of Study 1 support in clarifying the state of the art in DfAM, the associated opportunities and constraints, and thereby refining further research questions for the overall research. The process is detailed in Paper A.

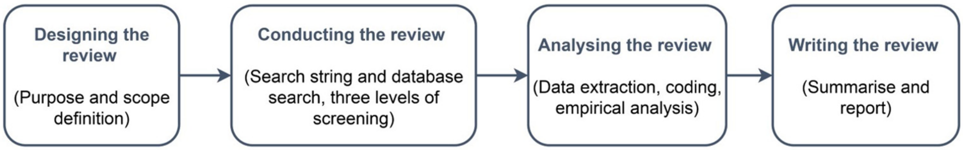


Figure 3.3: Methodology adopted for Study 1, adopted from Snyder (2019)

3.2.2 Study 2: Laboratory-based experiments

Focusing on one of the crucial design parameters, i.e., build/print orientation, the second study (Study 2) was conducted to investigate this parameter and its effects on the flexibility of lattice structures using quantitative methods. Laboratory-based experiments involving mechanical testing were adopted for data collection, wherein three open-celled strut-based lattice structures were printed and tested using uniaxial compression tests. The study was designed to ensure validity, e.g., by accommodating effects related to stress relaxation post testing, and by compensating for varying heights in the as-printed structures. Visual inspection and statistical calculations were used to analyse the experimental results. The process is further detailed in Paper B and a simplified illustration is presented in Figure 3.4. The compression test results were analysed using visual investigations and empirical calculations.

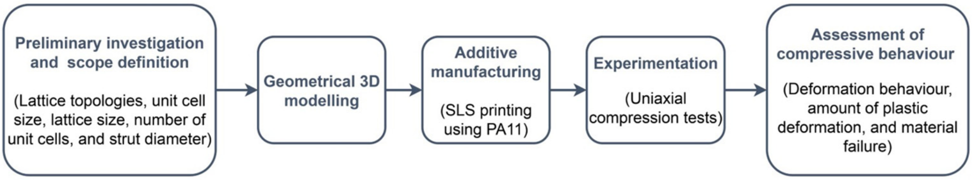


Figure 3.4: Methodology adopted for Study 2

3.2.3 Study 3: Laboratory-based and computation-based experiments

Focusing on another crucial factor, i.e., geometrical imperfections, usually seen in 3D-printed structures, the third study (Study 3) was conducted to investigate these imperfections and their effects on the flexibility of lattice structures using quantitative methods. Two sets of laboratory-based experiments were conducted on 3D-printed test artefact samples: one involving geometrical measurements and the other involving mechanical testing using uniaxial compression. The study was designed to ensure validity during experimentation, e.g., by eliminating any effects of print orientation or build plate positioning. The experimental results were utilised to calibrate a numerical model using computer-based finite element simulations in ANSYS, a commercial software for computational simulations, which was used to predict the compressive strength (an indicator of flexibility) of the samples.

A graphical analysis method was used to analyse the geometrical measurement results in the form of a radar chart. The compression test results, and numerical results were analysed using graphical analysis in MATLAB, a numeric computing software platform. The stiffness of the test stand used during the compression test was compensated for while analysing these results. The process is further detailed in Paper C and illustrated in Figure 3.5. Both the data from experiments and computations were compared using graphical analysis in MATLAB.

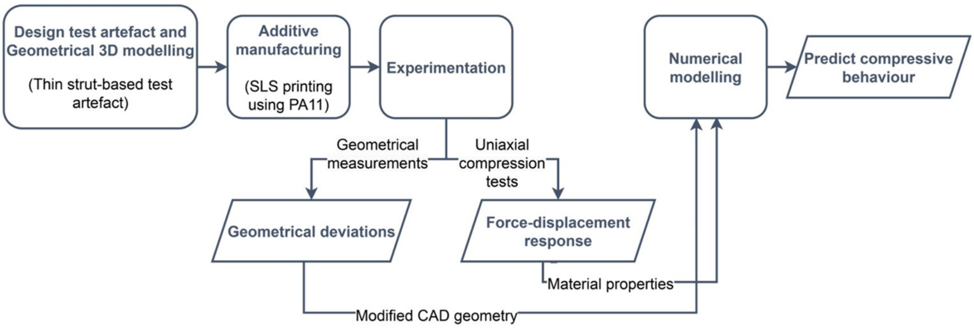


Figure 3.5: Methodology adopted for Study 3

3.3 Reflections on research quality and limitations

Validity and reliability are the two determinants that have been used to assess research quality in this thesis. Validity is about actually studying what is supposed to be studied (Kristina & Gustavsson, 2020), whereas reliability concerns the ability to repeat the study and get the same results, given the same conditions (Heale & Twycross, 2015; Yin, 2009). This research encompasses various studies, each employing different ways to ensure research quality across different stages of research. The initial study (Study 1) has been conducted using a rigorous and systematic approach in SLR to ensure research integrity. To minimise potential bias during data collection and analysis for Study 1, the active involvement of other researchers was ensured, thereby building confidence in the outcomes presented in Paper 1. In its entirety, each stage and the corresponding results of the SLR were documented, underscoring transparency and reliability, and judicious handling of electronic sources of evidence was exhibited. Studies 2 and 3 adhered to a detailed experimental procedure with documentation of any discrepancies observed during the experiments, as presented in the corresponding papers B and C, ensuring replicability. Preliminary experiments were conducted to validate the planned experimental setups before the main studies commenced. Papers B and C clearly delineated the research scope while also thoughtfully selecting materials, processes, and experimental setup to facilitate repeatability. Furthermore, prior to submission, senior researchers conducted peer reviews of the research outcomes in accordance with the recommendations made by Yin (2009), thereby enhancing the validity of the conducted studies. Throughout the research process, extensive documentation was diligently maintained, encompassing empirical data, video recordings of experiments, meeting minutes, coded and analyzed data, as well as a comprehensive record of data collection methods. This comprehensive documentation provides a clear and traceable account of the research trajectory, commencing with the initial research questions and culminating in the research conclusions.

While numerous measures have been undertaken to assure the quality of research, it is essential to acknowledge that, like any research, there exist certain limitations associated with the studies incorporated into this thesis. In the case of Study 1, considering the breadth and depth of the field of DfAM, the selection criteria and the subsequent classification of findings involved a subjective analysis, thus limiting reproducibility. Furthermore, the predefined dates within the search databases represent a limitation to the research outcomes as they restrict the volume of data available for analysis. Similarly, Study 2 involved the experimentation of a total of nine test samples for investigating deformation behaviour, and might need more samples for future investigations to ensure the validity of the presented results in Paper B. In Study 3, while the numerical simulations paved the way for realistically predicting the mechanical characteristics of thin structures, it should be noted that a finer resolution and the adoption of a more advanced finite element model are imperative to enhance prediction accuracy.

4 Summaries of appended papers

This chapter presents the results of the research by summarising the three papers appended in this thesis.

4.1 Paper A - Dual design for additive manufacturing in engineering design: A systematic literature review

The study presented in Paper A aims at presenting an overview of the research landscape from a dual DfAM perspective, as presented in Figure 4.1. The study involved a systematic literature review of 95 peer-reviewed journals and review papers published in English between January 2000 and March 2022. These publications were analysed using content analysis, grouping the findings into research clusters based on their core focus and main contribution. Further common patterns in each research cluster were grouped into their respective themes.

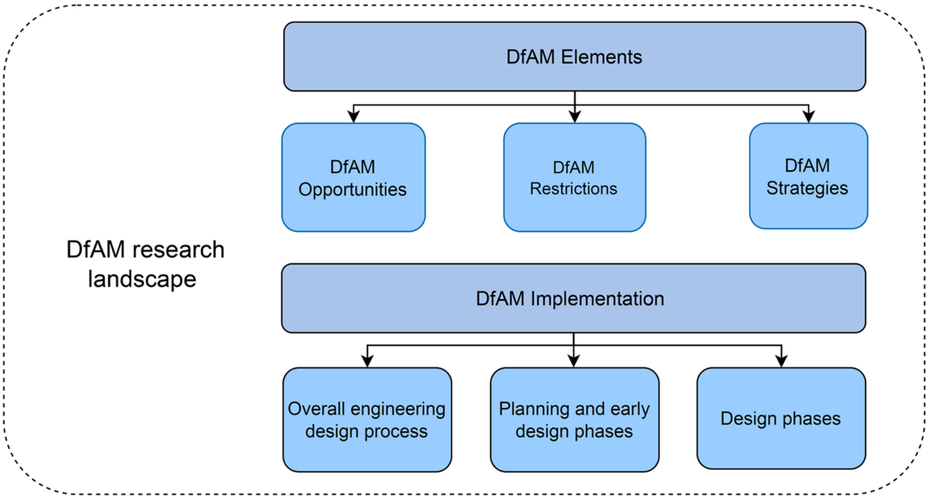


Figure 4.1: An overview of the research landscape from a dual DfAM perspective, Courtesy: Manuscript by Dash, S. et al. (2023)

The study also aims to identify the most- and least-researched areas when DfAM is specifically implemented in three of the design phases, i.e., conceptual, embodiment, and detail design of an engineering design process, presenting eight prominent themes shown in Figure 4.2. To identify the interconnections between these themes, pairwise theme combinations (i.e., analysing themes in pairs) were performed, providing insights on 52 theme combinations, as detailed in Paper A.

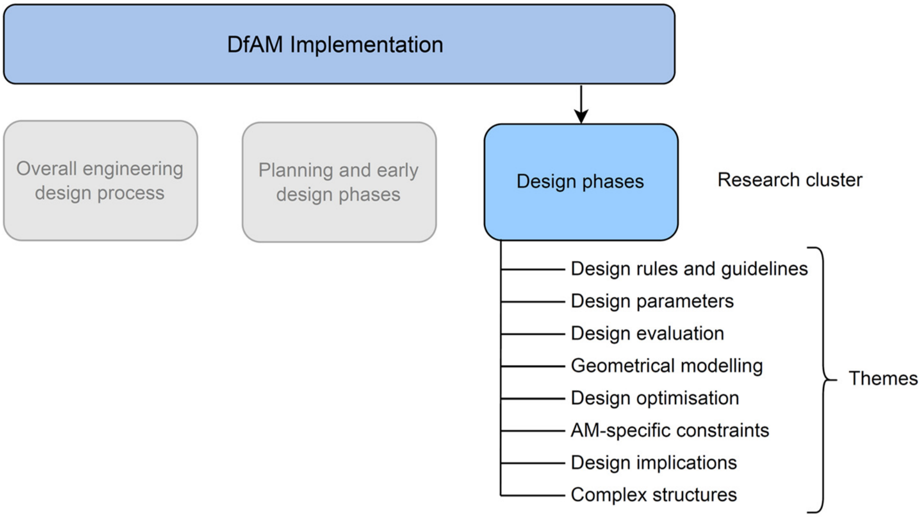


Figure 4.2: An example of themes derived from research clusters presented in Study 1

Presenting the findings from Paper A that contribute to this thesis, the design strategies belonging to the 8 research themes (in Figure 4.2) are discussed. These strategies support in *design optimisation*, *design evaluation,* and *geometric modelling*; enable incorporation of *design parameters* and *AM-specific constraints*; address the *design rules and guidelines* and *design implications* specific to AM and enable the design of *complex structures*. Within complex structures, the literature focusing on cellular structures contributes to the majority of research as compared to other complex structures such as compliant elements, foams, etc. When DfAM is concerned, different types of lattice structures and their variants, such as functionally graded lattice structures (FGLS), conformal lattice structures (CLS), and multi-material lattice structures are predominant in the literature as compared to the gyroid and Voronoi structures. The findings from the pairwise theme combination for the theme *complex structures* with each of the other themes reveal that the design strategies are mostly available for geometric modelling and FE-based design evaluation of lattice structures. Other available design strategies a) enable design optimisation specifically focusing on gradient based TO and multi-scale structural optimisation, b) address design implications, such as cost reduction, and

c) enable the incorporation of a few design parameters and AM-specific constraints. However, there is a scarcity of design strategies enabling manufacturing analysis-based design evaluation and other forms of design optimisation (e.g., size and parametric optimisation). Additionally, none of the available strategies address design rules and guidelines for lattice structures.

Although the SLR had certain inclusion criteria and limitations in terms of publication time and types, it presented a comprehensive overview of the DfAM research that adopt a dual DfAM perspective and successfully unveiled prominent research themes and their interconnections.

4.2 Paper B - Effects of print orientation on the design of additively manufactured bio-based flexible lattice structures

The study presented in Paper B aims at clarifying the design parameters and their significance in the design of flexible lattice structures. Specifically, it focuses on investigating lattice structure topologies and printing orientations specific to AM while keeping other lattice dimensions (e.g., unit cell size, overall lattice dimensions, and strut diameter) constant. The study involved 3D printing of various strut-based lattice structures with different topologies, including body-centered-cubic (BCC), a BCC variant with vertical struts (BCCZ), and face-centered-cubic (FCCZ), using PA 1101 and SLS technology. These lattice structures were printed in three different orientations (XY, XZ, and YZ) as shown in Figure 4.3, and their compression behaviour was experimentally investigated using uniaxial compression tests.

The study aimed at understanding the effects of printing orientation on the chosen lattice topologies in terms of their compressive behaviour, which serves as an indicator of the intended flexibility. The compressive behaviour was analysed in the form of deformation behaviour, and the amount of plastic deformation. Additionally, the occurrence of any visible material failures was also studied. While visual inspection was performed to assess their deformation pattern and material failures, plastic deformation was assessed mathematically by calculating their deformation percentages. The slightly varying heights of printed structures were compensated within the calculated percentages. To exclude any effects of stress relaxation, the printed structures were left to rest for 24 hours before measuring their deformed height.

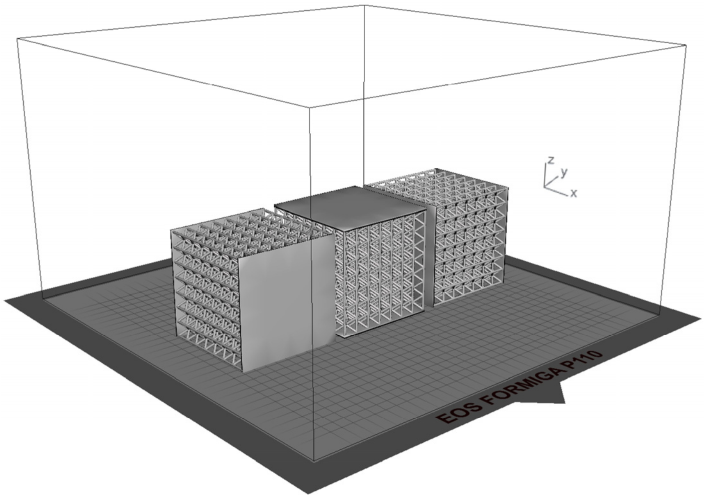


Figure 4.3: Printing of lattices in three different orientations: YZ, XY, and XZ, Courtesy: Dash and Nordin (2022)

The findings indicated that printing orientation had a substantial impact on deformation behaviour and material failure in these lattice structures, whereas it had no significant effect on the amount of plastic deformation. Instead, the topology of the lattice structures was identified as the primary factor influencing the amount of plastic deformation. A detailed presentation of the findings can be found in the full paper.

While further research with a larger sample size is necessary to fully explore compression behaviour, the findings of this study, as depicted in Figure 4.4, uncover the importance of printing orientation as a crucial design parameter when aiming to achieve flexible lattice structures.

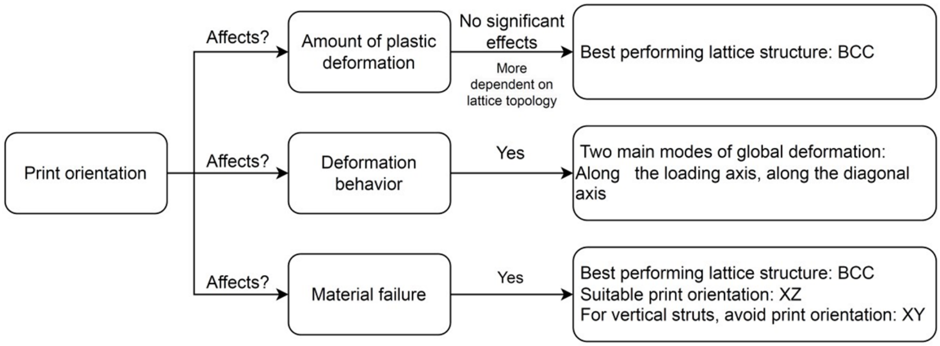


Figure 4.4: Effect of print orientation on the amount of plastic deformation, the deformation behaviour, and material failure in BCC, BCCZ, and FCCZ lattice structures

4.3 Paper C - Towards realistic numerical modelling of thin strut-based 3D-printed structures

The study presented in Paper C aims at clarifying the design parameters and AM-specific manufacturing constraints and incorporating their interactions by adopting a simulation-driven design approach. Specifically, it aims to develop a realistic numerical model by incorporating the geometrical and material deviations (i.e., manufacturing deviations) from the as-printed (or as-built) parts. Using the realistic characteristics of the as-printed parts, the numerical model can be used to accurately predict the compressive strength of a representative 3D-printed test artefact. The test artefact shown in Figure 4.5 (overall dimensions) was designed to represent thin strut-based structures, usually seen within lattice structures used for light-weighting applications. Test samples were 3D printed using PA 1101 and SLS technology. These samples were printed with a fixed orientation and positioned at the centre of the build plate, equidistant from each other, to eliminate any effects of print orientation or build plate positioning.

As the manufacturing deviations are more pronounced in thin struts, it is essential to accommodate these deviations when predicting compressive strength for the test samples. Geometrical deviations in the samples were measured and incorporated to modify the ideal CAD geometry; the modified geometry is shown in Figure 4.5.

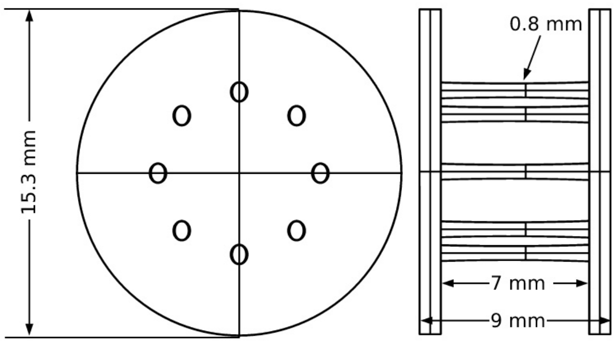


Figure 4.5: CAD model showing the elliptical cross-section and tapered strut geometry, Courtesy: Dash and Nordin (2023)

The compression strength of these samples was experimentally investigated using uniaxial compression tests, wherein the compressive strength was analysed by evaluating the force-displacement response and peak load. Material deviations were identified from the experimental results. Subsequently, experimental results were employed to calibrate the identified geometrical and material deviations into a numerical model. For simplicity, the calibration was performed using results from only two samples: one with the lowest peak load (sample 1) and another with the highest peak load (sample 4). The numerical model was used to predict the compressive strength of these test samples. Perturbations were added (i.e., disturbances added to the ideal model to replicate reality) to further enhance the prediction accuracy of this model. Details on the numerical modelling are presented in the full paper. The findings of this study indicated that the printed samples exhibited a tapered strut geometry with an elliptical cross-section, as shown in Figure 4.5. Further findings demonstrate that the force-displacement response and peak load measured from the experimental investigation tend to comply with those predicted using the proposed numerical model, as presented in Figure 4.6 and Table 4.1.

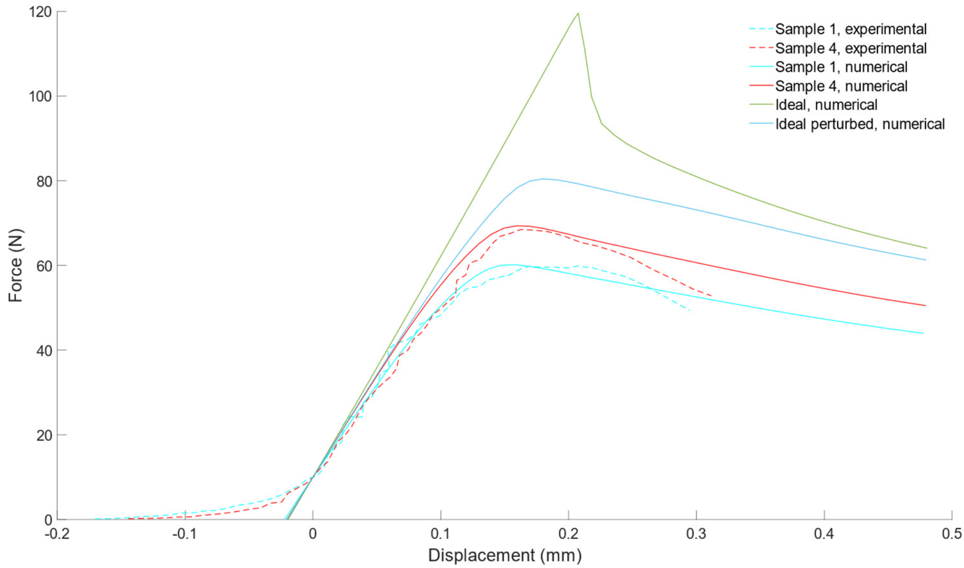


Figure 4.6: Force-displacement curves comparing the compressive behaviour of test samples obtained from experimentation and numerical simulations, Courtesy: Dash and Nordin (2023)

Table 4.1: Experimental and numerical results for peak load (numerical with *), Courtesy: Dash and Nordin (2023)

Result (N)	*Sample 1*	*Sample 1**	*Sample 4*	*Sample 4**	*Nonperturbed ideal*	*Perturbed ideal*
Peak load	59.88	60.19	68.50	69.37	119.58	80.44

Although a simplified numerical model was proposed in this study and has been limited to predicting samples' behaviour until the onset of plasticity, nevertheless, the outcomes of this study reflected the importance of modelling the geometric and material characteristics of as-printed parts using a simulation-driven design approach to accurately predict their compressive strength.

5 Discussions, conclusions and future research

This chapter presents and discusses the answers to the research questions, highlights the main research conclusions and contributions, as well as provides suggestions on the future research.

5.1 Discussions and conclusions

The research objective presented in this thesis was *to advance the state of the art in DfAM by enhancing knowledge on how to design flexible lattice structures specifically for AM*. Moreover, four research questions were formulated in Section 1.3 in order to fulfil the stated research objective. In this subsection, the outcomes from the three studies conducted as part of this thesis are discussed and research questions are answered, collectively fulfilling the aforementioned research objective, as summarised below:

RQ1: How do the existing design strategies within DfAM contribute to the design of lattice structures?

The studies in Paper A reveal that there exist design strategies in DfAM focusing on lattice structures, such as FGLS, CLS, functionally graded conformal lattice structures (FGCLS), multi-lattices (i.e., lattice structures with varying unit cell topologies), and multi-material structures. These strategies mostly assist in geometric or CAD modelling (e.g., creating solid or wireframe representations for multi-scale lattice structures and 3D structural reconstruction for variable density lattice structures) and FE-based design evaluation (e.g., validating material properties and structural performance in FGLS and CLS).

Some strategies also support design optimisation including gradient based TO (e.g., by incorporating manufacturing constraints in strut/truss-based lattice structures and by optimising variable density distribution in FGLS), and multi-scale structural optimisation (e.g., by enhancing mechanical performance and post-processing of FGLS geometries). Additionally, other strategies allow for the incorporation of AM-specific constraints (e.g., self-supporting lattice topologies), design parameters (e.g., build orientation, feature geometry), and address design implications (e.g., cost minimisation and accommodation of AM-induced anisotropy). Although, to some extent, the existing design strategies in DfAM address many aspects of lattice structures, the less-explored aspects include manufacturing analysis and other forms of design optimisation, such as size and parametric optimisation, as indicated by the findings in Paper A.

RQ2: What influencing factors may be considered when designing flexible lattice structures for AM?

Paper A provides an account of the most addressed influencing factors in the existing literature concerning lattice structures, i.e., the design parameters (print orientation, lattice geometry) and manufacturing constraints (geometric deviation, minimum feature size, slender members, support structures).

Due to the anisotropic nature of AM processes, the mechanical properties of printed parts are dependent on the print orientation, making it a crucial design parameter. While researchers have explored this dependency, few, if any, have studied the impact of print orientation on flexible lattice structures printed with PA 1101 using SLS. Paper B fills this research gap by investigating the effects of print orientation on structural flexibility of lattice structures. The findings in this paper highlight print orientation as an important design parameter for achieving flexible lattice structures. Delving into yet another important influencing factor, Paper C investigated manufacturing deviations, which is a manufacturing constraint, referring to the geometric and material deviations observed in as-printed parts. These deviations are even more pronounced in thin 3D-printed strut-based structures, typically seen in lightweight lattice structures, serving as a good way to achieve flexibility when desired. This makes it critical to account for these deviations when assessing their structural behaviour since their geometrical and material characteristics deviate from the base material(s) they are produced from. Recently, researchers have been shifting towards accommodating such deviations; however, few, if any, have studied manufacturing deviations and their impact on the design of thin strut-based structures printed with PA 1101 using SLS. The findings in Paper C suggest that if these deviations are accommodated in the design process, they can support in accurately predicting the compressive strength, which is an indicator of flexibility. The studies in Papers B and C highlight the significance of two influencing factors. However, a more comprehensive understanding of all such influencing factors (e.g., as identified in Paper A) will necessitate additional research.

RQ3: How do the interactions among the influencing factors affect the performance of such structures?

In Paper B, studies on three open-celled strut-based lattice topologies (BCC, BCCZ, and FCCZ) with fixed unit cell size (5mm), lattice size (35 × 35 × 35 mm), and strut diameter (0.8 mm), combined with three different printing orientations (XY, XZ, and YZ), revealed that printing orientation substantially impacted the deformation behaviour and the amount of material failure. However, it had no significant effect on plastic deformation, which was instead primarily influenced by lattice structure topologies – another design parameter addressed in the literature as per findings in Paper A. In contrast to the variable print orientation considered in Paper B, the studies in Paper C consider a fixed orientation to avoid any associated effects. The focus of these studies was to investigate manufacturing deviations (i.e., a manufacturing constraint) in terms of geometric and material deviations in as-printed test artefacts representing thin strut-like features commonly seen in lattice structures. As observed in Paper A, geometric deviations such as the real fillet-edge shape of struts are influenced by the lattice topology and affects elastic properties in strut-based lattice structures. In Paper C, the observed geometrical deviations included a tapered strut geometry with an elliptical cross section, and material deviations included variations in Young's modulus and yield strength compared to the base material. These deviations together influenced the compressive strength of the printed samples. Together, the experimental and numerical studies conducted in Papers B and C provide some insights into influencing factors, their interactions, and their effect on the flexibility of lattice structures. Nonetheless, they may not comprehensively address all essential influencing factors, their interactions, and their effects.

RQ4: How can the influencing factors be incorporated while designing flexible lattice structures for AM?

Two influencing factors, i.e., printing orientation and manufacturing deviations, and their effect on the design of flexible lattice structures were investigated in Papers B and C respectively. The studies in Paper C further attempted to incorporate one of these factors, i.e., manufacturing deviations in the design process, and assess their effect on the compressive strength of a test artefact representing thin strut-like features commonly seen in lattice structures. This was done by employing finite element-based numerical modelling, typically employed for simulation-driven design. From Paper A, it has been observed that numerical methods are either used in the design of lattice structures by incorporating design parameters or manufacturing constraints within them or are used for the evaluation of their mechanical properties. Studies in Paper C attempt to involve numerical modelling for integrated design and evaluation. Therefore, in this paper, a numerical model with realistic characteristics was developed by calibrating with the geometric and material deviations observed from experimental studies. It was observed that the prediction accuracy was improved by incorporating these manufacturing deviations into the numerical model instead of using the as-designed CAD model for geometry and using base material properties. While Paper C suggests direct numerical modelling as one approach, it does not exclude other methods, like homogenization methods (Dong et al., 2017), which could also be viable, although these methods may not precisely capture manufacturing influences.

5.1.1 Fulfilment of research objective

The three studies in Papers A, B, and C collectively addressed four research questions to fulfil the research objective. The outcomes of this thesis lay the foundation for designing flexible lattice structures, specifically tailored for AM, by providing insights into the available design strategies for lattice structures, revealing key information on influencing factors, i.e., design parameters and manufacturing constraints, and demonstrating the feasibility of incorporating these factors using finite element-based numerical modelling. Collectively, these outcomes establish the groundwork for developing future design approaches that can facilitate the design of the intended flexible lattice structures.

5.1.2 Research contribution

Within this thesis, it was found that the existing literature in DfAM concerning product design primarily concentrates on maximising stiffness with simultaneous weight reduction, such as Dalpadulo et al. (2020) and Diegel et al. (2020), while the domain of flexibility remains under-explored, with limited instances such as Air and Wodehouse (2023) and Park and Park (2020) touching upon DfAM at a surface level. A significant contribution of this thesis lies in delving into this under-explored area through the design of flexible lattice structures by providing valuable insights into the design strategies available for lattice structures (e.g., type, scope, and potential shortcomings) that are adaptable or expandable to the realm of flexible lattice structures. Moreover, the outcome of this thesis contributes to research by providing an improved understanding of influencing factors, e.g., print orientation, manufacturing deviations, and their effect on compressive behaviour (i.e., flexibility indicator). Building upon existing literature efforts in numerical modeling and simulations for lattice structures by Vrana et al. (2022) and Tkac et al. (2020), another contribution involves finite element-based numerical modelling as an integrated design approach incorporating the aforementioned factors when designing flexible lattice structures tailored for AM. Furthermore, while the current research in AM predominantly focuses on lattice structures printed with the ME process (Obadimu & Kourousis, 2021), the empirical studies in this thesis advance these efforts by focusing on lattice structures printed with the SLS process using bio-based polymers, and providing improved understanding of the characteristics of printed parts, such as geometric and material deviations, and assessing their effects on the resulting structural performance, such as compressive strength.

The practical contribution of this thesis involves creating knowledge for engineering designers and practitioners that can assist them in the creation of flexible lattice structures for industrial applications demanding flexibility, such as upholstery design in furniture, foot orthotics for patients, etc. Moreover, it attempts to provide the industry with insights into the influencing factors that are crucial when designing such structures. How these factors can affect ‘flexibility’ and/or related structural performance will assist the industry in iterating on different design concepts depending on the desired specification. For example, as observed in Paper B, when material robustness is most valued, XZ orientation is the suitable print orientation, whereas XY is recommended to be avoided when lattice structures involve vertical struts, and when flexibility is most valued, BCC is the suitable lattice topologies among the studied ones.

Additionally, the research attempts to provide insights into the geometrical and numerical modelling of flexible lattice structures. In terms of geometrical modelling, it emphasises on the design tolerance and provides an indication of the tolerance that should be considered in an ideal CAD model, for instance, a 9% deviation on the cylindrical strut diameter of 0.8mm was observed when dealing with thin strut-based flexible lattice structures, as shown in Paper C. The numerical modelling presented in the research attempts to assist the engineering designers or simulation engineers to suitably assist in the design and analysis of similar thin strut-based structures, as shown in Paper C, in the future.

5.2 Future research

This thesis has explored the domain of DfAM to broaden its scope by venturing into the design of flexible lattice structures. However, to develop a comprehensive approach for designing these structures for practical industrial use, there remains substantial work to be carried out in the future. In this regard, the following include the important areas for potential future research:

- *Development of the SDD approach*

  - This thesis provides valuable insights for assisting in the design of flexible lattice structures (represented by the green outline in Figure 5.1). Future work entails the formulation of a SDD approach using FE simulation-based numerical modelling to facilitate the design of flexible lattice structures by combining the topics addressed in this thesis with other related unexplored ones (represented by the yellow outline in Figure 5.1) ones. Practical realisation of such an approach will require advanced numerical modelling, extensive experimentation and establishing appropriate links between different elements of the SDD approach.

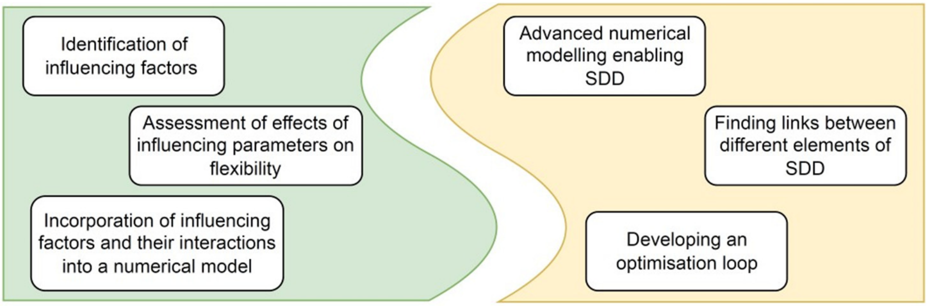


Figure 5.1: Explored (in green) and unexplored (in yellow) topics in this thesis that can be potentially combined to formulate a future design approach to design flexible lattice structures for AM

- Additionally, a SDD approach can be extended to develop a design optimisation loop for stimulating new design concepts, thereby guiding towards optimal design and supporting relevant decision making. For instance, based on the predicted compressive behaviour or strength using the numerical model, design parameters and manufacturing constraints in flexible lattice structures can be adjusted until the desired flexibility or related performance is obtained.

- *Advanced numerical modelling*

- Numerical modelling using FE simulations has been widely used for the evaluation of the structural behaviour of parts. However, future work aims to perform integrated design using simulation, complying with the essence of SDD, instead of using them only for evaluation at the end of a design process. Although a numerical model has been developed as presented in Paper C, it is a simple model that utilises a perfectly plastic material model, involves 3D coarse mesh elements of 0.3mm, and considers simplified loading as well as boundary conditions. In order to simulate complex problems with increased prediction accuracy, the numerical model requires further development to include an accurate material model, modelled using finer mesh, and mimic complex loading scenario (for example, multiple load cases instead of uniaxial loading), boundary conditions (for example, modelling the interfaces with the loading surface or volume depending on the target application), and so on.

- Additionally, the numerical model presented in Paper C is limited to predicting the structural behaviour only until the onset of plasticity and hence needs further improvement to capture the phenomena beyond the plasticity onset. Assessment of failure modes under varying loading conditions can also possibly support improving numerical modelling.

- *Advanced lattice designs with varying material combinations*

  - For the sake of simplicity and due to the preliminary nature of the investigation, the scope of this thesis has been limited to thin strut-based lattice structures, such as BCC, BCCZ, etc. However, since lattice geometry (e.g., lattice size and topologies) is a design parameter that affects flexibility, there is a possibility to broaden the scope by investigating varying geometries, i.e., different lattice sizes, unit cell sizes, and lattice topologies. Currently, few lattice topologies have been investigated in Paper B; however, other parameters such as lattice size and strut diameter have been kept fixed. Additionally, there have been studies on lattice structures with variable density distribution, as reported in Paper A, so it might be interesting to venture into such lattice structures, which might allow for controlled flexibility in only certain areas of lattice structures instead of the whole structure.

  - Futher, the studies presented in this thesis have been limited to only one material, i.e., a bio-based polyamide, PA 1101, which was selected to get a sustainable advantage compared to other available 3D printable materials. Other suitable alternatives have not yet been explored, which might serve as a better alternative to the currently used PA 1101. However, commercial availability and limited scaled-up in-house material production in Kemicentrum, LTH might affect such investigations.

- *Design recommendations*

  - In general, there is a lack of design recommendations for lattice structures within the context of DfAM, as has been highlighted in Paper A. One of the key aspects of the presented research involves the identification of influencing design parameters and AM-specific manufacturing constraints that might affect the flexibility and performance of lattice structures. Based on the investigations of these factors, some design recommendations can be presented, e.g., recommendations on an acceptable range for manufacturing constraints. The studies performed in this thesis involved the investigation of two of the influencing factors within two empirical studies that individually present design recommendations, such as the selection of a suitable print orientation in Paper B or an appropriate design tolerance in Paper C. Further studies should investigate other such factors and focus on providing design recommendations when flexible lattice structures are concerned.

- *Performing scale-up studies within industries*

  - The studies performed in this thesis have not been used in industrial case studies, as this will require development of scaled-up prototypes. Hence, the feasibility of scaling up the current findings and apply them to demonstrator projects has to be finalised prior to conducting such case studies. As part of the STEPS project, the plan is to build several 1:1 or reduced-scale demonstrator prototypes for upholstery during the Orgatec trade fair in Sweden in the upcoming year.

- Further actual realisation and acceptance of the outcomes of the presented research within industry might be dependent on the industrial users, which would require testing the usability of the outcomes within the users' context.

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