Design for additive manufacturing of flexible lattice structures

A simulation driven design approach

Dash, Satabdee

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Satabdee Dash

DOCTORAL DISSERTATION

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Abstract:

Additive manufacturing (AM) makes it feasible to realise complex lattice structures that provide structural flexibility through engineered structural design rather than relying solely on material softness. Across sectors such as furniture, healthcare, protective equipment, and robotics, such flexibility is a core functional requirement, that influences comfort, fit, impact response, lightweighting, and functional integration, thereby making the design of flexible lattice structures particularly appealing. While prior AM research has largely focused on lightweight, stiffness-oriented lattices, systematic design for controlled structural flexibility remains underdeveloped. This gap is amplified when sustainability goals push material selection toward stiffer bio-based polymers instead of typical elastomers. In this context, geometry-driven flexibility provides a way to achieve structural flexibility that addresses both performance and environmental objectives while integrating AM-specific considerations throughout the design process.

This dissertation investigates the design of flexible strut-based lattice structures using a simulation-driven design (SDD) approach centered on dual design for additive manufacturing (DDfAM). Through DDfAM, it integrates geometry parameters, material behaviour, and manufacturing constraints directly into the design process to realise functional, manufacturable lattice structures with engineered geometry-driven flexibility. The dissertation comprises of five inter-related peer-reviewed studies that combine systematic literature review, numerical modelling, and experimental validation using selective laser sintering of bio-based polyamide, PA11.

The dissertation identifies key factors governing structural flexibility: lattice size and geometry, strut thickness & orientation, print orientation, and manufacturing deviations, while quantifying their effects, for instance, variations in as-printed materials' stiffness due to strut orientation changes. It develops and refines finite element-based numerical models through experimental calibration for accurate strut- and lattice-level predictions, especially for thin struts near manufacturability limits. It demonstrates how geometry-driven flexibility can be used to replicate foam-like flexibility using stiffer bio-based material. Building on these findings, it proposes an SDD approach to design bio-based flexible lattice structures, specifically for AM and presents a case exemplification for a real-world component.

The main contribution of this dissertation lies in demonstrating how SDD can bridge design intent and manufacturability for flexible lattice structures. By enabling geometry-driven flexibility to develop bio-based design alternatives, it broadens both the material and application space for additively manufactured lattice structures and provides a structured design approach for engineering applications that require structural flexibility.

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

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"The more I live, the more I learn.

The more I learn, the more I realise the less I know"

(Michel Legrand)

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Satabdee Dash
Lund, February 2026

Abstract

Additive manufacturing (AM) makes it feasible to realise complex lattice structures that provide structural flexibility through engineered structural design rather than relying solely on material softness. Across sectors such as furniture, healthcare, protective equipment, and robotics, such flexibility is a core functional requirement, that influences comfort, fit, impact response, lightweighting, and functional integration, thereby making the design of flexible lattice structures particularly appealing. While prior AM research has largely focused on lightweight, stiffness-oriented lattices, systematic design for controlled structural flexibility remains underdeveloped. This gap is amplified when sustainability goals push material selection toward stiffer bio-based polymers instead of typical elastomers. In this context, geometry-driven flexibility provides a way to achieve structural flexibility that addresses both performance and environmental objectives while integrating AM-specific considerations throughout the design process.

This dissertation investigates the design of flexible strut-based lattice structures using a simulation-driven design (SDD) approach centered on dual design for additive manufacturing (DDfAM). Through DDfAM, it integrates geometry parameters, material behaviour, and manufacturing constraints directly into the design process to realise functional, manufacturable lattice structures with engineered geometry-driven flexibility. The dissertation comprises of five inter-related peer-reviewed studies that combine systematic literature review, numerical modelling, and experimental validation using selective laser sintering of bio-based polyamide, PA11.

The dissertation identifies key factors governing structural flexibility: lattice size and geometry, strut thickness & orientation, print orientation, and manufacturing deviations, while quantifying their effects, for instance, variations in as-printed materials' stiffness due to strut orientation changes. It develops and refines finite element-based numerical models through experimental calibration for accurate strut- and lattice-level predictions, especially for thin struts near manufacturability limits. It demonstrates how geometry-driven flexibility can be used to replicate foam-like flexibility using stiffer bio-based material. Building on these findings, it proposes an SDD approach to design bio-based flexible lattice structures, specifically for AM and presents a case exemplification for a real-world component.

The main contribution of this dissertation lies in demonstrating how SDD can bridge design intent and manufacturability for flexible lattice structures. By enabling geometry-driven flexibility to develop bio-based design alternatives, it broadens both the material and application space for additively manufactured lattice structures and provides a structured design approach for engineering applications that require structural flexibility.

Popular science summary

Additive manufacturing (AM) or 3D printing is revolutionising part design by building them layer-by-layer, unlike conventional techniques that carve away material from solid blocks. This freedom enables intricate shapes and complex geometries such as lattice structures which consist of repeating 3D network of interconnected struts.

So far, these lattice structures have seen widespread use in stiff, lightweight parts, for example, in aerospace or high-performance engineering. But everyday items rely on structural flexibility: think comfortable furniture upholstery, custom-fit medical insoles, cushioning in helmets, or adaptable robotic grippers. Today, such flexibility is usually obtained by using soft materials like foams or similar elastomers. While these materials work well, they can wear out, lose shape over time, and most importantly, rely on fossil resources, which raise environmental concerns. Sustainable bio-based plastics offer a greener alternative, yet most are typically stiffer, creating a design challenge. One possible path forward is to create flexibility through geometry instead of material softness.

This dissertation, simply put, addresses this challenge by investigating: *Can we design flexibility into the structure itself, independent of material softness?* This possibility is demonstrated through five peer-reviewed studies, which involve a mix of literature reviews, test artefact designs, computer-based modelling and simulations, and physical testing of printed test samples - all using selective laser sintering, a powder-based 3D printing technique, with bio-based polyamide material, PA11.

By carefully choosing the strut orientation, thickness, and layout, the dissertation shows that it is possible to design flexible lattice structures, even though the base material is not soft. Importantly, flexibility is influenced not only by geometry, but also by how the part is 3D printed. Printing orientation and small manufacturing deviations can significantly affect structural behaviour, especially in thin-strut lattices. This highlights the importance of dual design for AM - a concept that promotes simultaneous consideration of design and manufacturability within the design process. Building on this concept, the dissertation proposes a simulation-driven design approach for designing flexible lattice structures specifically *for* AM. Through five studies, it reveals how geometry, material behaviour, and manufacturing constraints interact, integrating these insights into the approach.

The findings demonstrate that stiff, bio-based polymers like PA11 can be used to create 3D-printed flexible lattice structures, exploiting geometry-driven flexibility as an alternative to standard foams. By uncovering key factors, i.e., lattice size and topology, strut thickness & orientation, print orientation, and manufacturing deviations and by quantifying their effects on performance, the dissertation strengthens the link between design and manufacturing in AM. Building on these

insights, it provides engineers with a practical pathway for developing sustainable and manufacturable lattice structures for everyday and advanced applications, including furniture, healthcare, protective gear, and robotics, while minimising trial-and-error.

List of appended papers

Paper A
Dash, S., Nordin, A., and Johansson, G. (2025). *Dual design for additive manufacturing in engineering design: a systematic literature review*, Rapid Prototyping Journal. Vol. 31, No. 11, pp. 40-61.

Author contributions:

Satabdee Dash collaborated with the co-authors in conceptualising and designing the study. She led the data collection and abstraction and was also responsible for data curation. All co-authors participated in the literature screening and contributed to the successive refinement of the research design. Data analysis and synthesis were guided through multiple rounds of joint discussions, and the co-authors provided valuable input in structuring and presenting the results. Glenn Johansson contributed from an overall methodological perspective, while Axel Nordin provided subject-specific technical expertise and supported part of the quantitative analysis. As lead author, Satabdee Dash prepared the original manuscript, including all visualisations and references. She coordinated and implemented the revisions in collaboration with the co-authors and served as the corresponding author throughout the review and publication process.

Paper B
Dash, S., Nordin, A. (2022). *Effects of print orientation on the design of additively manufactured bio-based flexible lattice structures*. In: Proceedings of NordDesign 2022. Design Society, Copenhagen, Denmark, pp. 1–12.

Author contributions:

Satabdee Dash led the conceptualisation and research design in collaboration with the co-author. She participated in the experimental planning together with Axel Nordin and was responsible for conducting the experiments. She carried out the primary data analysis and led the presentation of the results. Axel Nordin contributed to the interpretation of the findings and provided critical input on the analysis and presentation. The discussion of the results, including the formulation of design implications and conclusions, was undertaken jointly. As lead author, Satabdee Dash drafted the original manuscript, including all visualisations and references, and implemented the revisions based on feedback from Axel Nordin and the conference reviewers. She also presented the paper at the conference.

Paper C

Dash, S., Nordin, A. (2023). *Towards realistic numerical modelling of thin strut-based 3D-printed structures*. In: Proceedings of the International Conference on Engineering Design (ICED23). Design society, Bordeaux, France, pp. 3591–3600.

Author contributions:

Satabdee Dash led the conceptualisation and research design in collaboration with the co-author. Both authors contributed to the design of test artefacts, as well as the experimental planning and setup. Satabdee took the responsibility for modelling the artefacts, performing mechanical testing, and taking measurements. She carried out the data collection and conducted the primary analysis of the experimental data. The numerical simulations were performed jointly by the authors, with iterative refinements undertaken for finalising the study outcomes. Axel Nordin led the analysis of the numerical results. Both authors contributed equally to the interpretation and presentation of the findings. As lead author, Satabdee Dash drafted the original manuscript, including all visualisations and references, and implemented the revisions based on feedback from the co-author and conference reviewers. She also presented the paper at the conference.

Paper D

Dash, S., Nordin, A. (2026). *A combined experimental – numerical approach for predicting Young's modulus in additively manufactured thin strut-based structures.* International Journal of Advanced Manufacturing Technology. Vol. 142, pp. 3392-3406.

Author contributions:

The study was conceptualised and designed jointly by both authors. Satabdee Dash led the design and modelling of the test artefacts and was primarily responsible for planning and executing the experimental work, including setup and testing. She also managed the curation of the collected data. The experimental procedures were refined through multiple rounds of discussions and collaborative decision-making between the authors. Both authors independently conducted numerical simulations and compared their respective approaches to establish a reliable and robust modelling strategy. The analysis and interpretation of the results were carried out jointly. As lead author, Satabdee Dash drafted the original manuscript, including all figures and references. She coordinated the revision process in collaboration with the co-author and served as the corresponding author throughout the peer-review and publication process.

Paper E

Dash, S., Nordin, A. (2026). *Designing flexible lattice structures for additive manufacturing: A simulation-driven design approach*. Manuscript to be submitted to a journal.

Author contributions:

The study was built upon preliminary experiments conducted by Satabdee Dash, which laid the foundation for the research. The conceptualisation, overall research design, and methodological planning were developed through collaborative discussions, with Satabdee Dash leading the process. She led the experimental investigations, 3D modelling, data analysis, and the realisation of the product-level demonstrator for a furniture headrest, with input and feedback from Axel Nordin. Axel Nordin played a key role in designing and structuring the numerical environment supporting the study, which was subsequently further developed, implemented, and operationalised by Satabdee Dash. Both authors worked together to validate the numerical model and compile the results. As lead author, Satabdee prepared the original manuscript, including formatting and referencing. Both authors contributed to synthesising and interpreting the results and preparing visualisations. Axel Nordin further contributed to the theoretical framing, supported methodological refinement, provided scientific supervision, and contributed to drafting and critically revising the manuscript. All results and conclusions were discussed and agreed upon jointly.

1 Introduction

This chapter presents the background, problem statement, and objectives of the research[1], followed by research questions and research scope.

1.1 Background

In recent years, manufacturing has been reshaped by rapid technological progress and a growing awareness for sustainable practices. As industries strive to align with the United Nations' Sustainable Development Goals (SDGs), technological innovation has become a driving force in making the manufacturing systems stronger, more efficient, and better for the environment [1]. Against this backdrop, the emergence of the fourth industrial revolution, often referred to as Industry 4.0, represents a major turning point in the way manufacturing operates. This era brings together digital and physical technologies such as artificial intelligence, robotics, the internet of things (IoT), and additive manufacturing (AM) to create production environments that are smarter, more connected, and capable of adapting to ever-changing demands.

The adoption of AM has introduced a new dimension to sustainable manufacturing by enabling decentralised production and reducing waste, material usage, lead time (e.g., in spare part production) and manufacturing costs (e.g., in low volume production) [2, 3]. Additive manufacturing, also referred to as three-dimensional printing (3DP), was first developed in the late 1980s [4] and is defined by the American Society for Testing and Materials (ASTM) and the 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"*[5]. The ability of AM to create sophisticated products with advanced attributes such as novel materials, complex geometries, hierarchical structures, and functional assemblies [6] has resulted in significant advancements in the aerospace, manufacturing, and biomedical industries [4].

[1] Partly based on Dash (2023) *Design of flexible lattice structures. A design for additive manufacturing perspective* (Licentiate Thesis), Lund University, Lund, Sweden

Due to the opportunities offered by AM, it has transformed from rapid prototyping into a production technology [4, 7]. However, in comparison to conventional production technologies, AM shows inferior performance with regard to manufacturing speed, accuracy, repeatability, and cost [8]. Aside from that, AM has its own set of constraints, such as the need for support structures and post-processing, making it important for the product designs to be optimised for both the opportunities and constraints specific to AM [9]. This, in turn, led to the extension of conventional Design for Manufacturing (DfM) and Design for Assembly (DfA) to Design for Additive Manufacturing (DfAM) in order to fully leverage the unique characteristics associated with AM [10].

Building on this, DfAM has been approached in the literature through different perspectives depending on whether design decisions account for AM opportunities and constraints. Accordingly, three types have been identified by Laverne, et al. [11]: (a) opportunistic DfAM, which focuses on harnesses opportunities offered by AM; (b) restrictive DfAM, which prioritises the incorporation of AM manufacturing constraints; and (c) dual DfAM, which considers both AM opportunities and constraints within the design process.

The field of DfAM has grown rapidly over the past decade, attracting increasing attention from researchers and practitioners, with numerous studies exploring different aspects of DfAM, from design principles and optimisation techniques to industrial applications [9, 12-14], thus advancing the field. Many of these works involve part design or redesign, often within industrial case studies, where DfAM concepts are applied to adapt conventional parts for AM or to improve existing AM components [15, 16]. With the growing industrial interests in generating lightweight stiff structures using AM, a majority of these studies have primarily focused on design objectives of reducing weight and enhancing mechanical performance like strength or stiffness [15, 17-19]. However, other objectives, especially structural flexibility, which is important for applications like furniture upholsteries, soft robotics, and protective gears, have received comparatively little attention [20, 21]. Structural flexibility enables parts to deform predictably under load, improves comfort, reduces assembly complexity, integrates multiple functions, and enhances durability, providing significant functional and industrial value [22, 23]. When flexible structures are considered for DfAM, they can promote circular economy principles as well. Consolidating components into single, monolithic, flexible parts not only simplifies assembly and reduces material use but also helps minimise environmental impact throughout production and product life [24-26].

Despite advances in the field of DfAM, like any other manufacturing technologies, the extent to which the desired mechanical performance can be attained is limited by the manufacturing constraints specific to AM. Addressing these limitations often requires considering both the opportunities and constraints inherent to AM. The concept of dual DfAM, as previously mentioned, promotes such an integrated practice of designing parts while considering their manufacturing using AM [27].

This, in turn, helps designers to better exploit the unique capabilities of AM while ensuring manufacturability, thereby realising its true potential [11]. While the literature widely reports work that addresses either AM opportunities or constraints in isolation, fewer methods explicitly consider both aspects concurrently [11]. In particular, Laverne, et al. [11] reported that work classified as dual DfAM accounts for approximately 30% of those identified in the literature, highlighting the neglect despite clear relevance.

Dual DfAM not only supports better adoption of AM by designers and engineers [28], but also improves manufacturability [29], for instance, by enabling complex yet printable geometries and promotes product innovation through improved performance and added value for end users [11]. Given the significance of adopting such a concurrent perspective, this thesis focuses on dual DfAM. Within this work, dual DfAM is treated as a design concept that promotes an *integrated practice of simultaneously addressing AM opportunities and manufacturing constraints to fully leverage the unique capabilities of AM while ensuring manufacturability*.

For clarity and consistency, this interpretation is referred to as DDfAM throughout the thesis and is adopted as the central focus of this work.

To complement DDfAM, Simulation-Driven Design (SDD) offers designers a way to explore and refine ideas virtually, helping them make better design decisions before printing. Within the engineering design process, SDD approaches have been widely adopted to enhance part performance and manufacturability [30-33]. When applied to the design of mechanical systems, SDD typically relies on finite element analysis (FEA) to numerically predict the mechanical behaviour of a design under specific loading conditions. This enables designers to iteratively evaluate, modify, and validate designs both early in the design process and for final validation. These simulation-based approaches are often used for design optimisation to achieve desired performance objectives; typically embedded within the topology optimisation environment [34-36]. In addition to optimising geometries for performance [37, 38], FE-based numerical modelling within constrained optimisation environments has further allowed AM-specific constraints, such as feature size thresholds and printing orientation, to be integrated [39-41]. Together, these capabilities highlight the strong potential of SDD in supporting DDfAM implementation.

Despite these advances, challenges remain. The layer-by-layer nature of AM often leads to differences between as-designed and as-printed parts, highlighting the need for closer alignment between simulation and experimentation to improve design accuracy and reliability [42, 43]. Such an integrated simulation-experiment design loop, where virtual predictions and experimental results continuously inform each other to refine the model, can provide deeper insight into material behaviour, process limitations, and the real performance of 3D-printed parts [33]. Yet this integration is still limited in current DDfAM and SDD research, indicating the need for design approaches that can capture the complex relationships between geometry, material, and manufacturing process in AM.

1.2 Problem statement

When it comes to achieving structural flexibility, several types of flexible structures have been developed, including adaptive [44], deployable [45], and compliant structures [23]. Among these, compliant structures are particularly common, as they use flexible elements instead of traditional joints to enable movement. This approach helps reduce wear, simplify assembly, and integrate multiple functions within fewer parts [23, 46].

Flexibility can also be achieved through mechanical metamaterials which are engineered structures designed to exhibit specific properties that differ from those of their base materials [47, 48]. Examples include origami- [44] and kirigami- [49] based metamaterials which use folding or cutting patterns to control the motion. Among the different types of metamaterials, lattice structures have gained particular attention because their geometric arrangement offers high design freedom, tunable mechanical properties, and computational efficiency. These advantages, along with other relevant aspects, are discussed further in Section 1.4.

Application areas that demand structural flexibility include robotics (e.g., locomotion systems), healthcare (e.g., foot orthotics), aerospace (e.g., aircraft propellers and panels), and shock absorption (e.g., cranial helmets), among others. Flexible lattice structures have gained significant attention in these industries because they act as engineered materials whose internal geometry can be tailored to achieve desired mechanical responses. The term, *flexibility,* in this thesis*, refers to structural flexibility arising from geometry rather than material softness.* Here, material softness refers to the inherent softness of the material, characterised by low elastic modulus. Structural flexibility has been approached in different ways within existing research. Examples include the design of multi-material compliant lattice-structured beams [50], functionally graded structures inducing flexibility through metamaterial design [51], and the design of shape-morphing geometric lattices [52].

Additive manufacturing, comprising a family of layer-by-layer fabrication processes, including material extrusion, VAT photopolymerisation, and powder bed fusion [5], has become a preferred way for manufacturing such complex lattice geometries. Most of the flexible lattice structures reported to date, however, are fabricated using elastomeric materials such as thermoplastic polyurethane (TPU) [53] or resin-based photopolymers [54]. These materials are popular because their inherent softness simplifies the design of flexible components; for example, 3D-printed foot insoles by Carbon© [55] leverage elastomeric properties to achieve comfort and compliance. While this material-driven approach to flexibility has proven effective, it also restricts the design space to a narrow range of mechanical behaviours that depend heavily on the viscoelastic properties of the base material. Moreover, elastomeric flexible lattice structures often face challenges such as creep, dimensional instability, and limited sustainability owing to their fossil-based origins [56].

To broaden the material palette and improve environmental sustainability, there is a growing interest in bio-based polymers [57] such as PA 1101, a castor oil-derived polyamide known for its stiffness, recyclability, and lower carbon footprint [58], that can serve as a sustainable alternative to widely used materials like polyurethane (PUR) foams. However, such bio-based materials are traditionally more rigid compared to soft elastomers. As a result, designing flexible lattice structures using stiff bio-based polymers remains challenging. However, this introduces an opportunity to design geometry-driven flexibility, where unit cell topology, strut thickness, and lattice gradients are strategically varied to achieve compliant behaviour without relying on inherently soft materials. This geometry-driven design space can be realised using laser powder bed fusion (L-PBF) processes, in particular selective laser sintering (SLS), which is adopted in this thesis. By doing so, flexibility can be customised structurally while enhancing strength and sustainability impacts. Although a few bio-based elastomeric materials (e.g., Desmopan® Eco, Pebax®) exist and are 3D printable, their use in lattice structures remain limited. Additionally, printing such elastomers still poses practical issues, such as stringing or poor dimensional control in Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM) processes [59, 60] that can, to some extent, be mitigated through L-PBF processes like SLS.

These material-related challenges directly affect how flexible lattice structures are designed, making the design process just as critical as material selection. However, much of the existing research treats AM mainly as a fabrication method to produce these structures [61, 62] or to modify existing AM parts for improved flexibility [63], rather than *designing structures specifically for AM*. While flexibility as a mechanical property has been investigated previously [64-66], only a small number of studies have incorporated DDfAM considerations in the design process, although to a limited extent [20, 21, 67]. Consequently, there is limited research that has explored how design parameters (e.g., lattice topology) can be optimised in conjunction with AM-specific manufacturing constraints (e.g., printing orientation) to achieve desired levels of structural flexibility. Furthermore, the current research efforts have mostly involved L-PBF-based metallic and material extrusion (ME)-based polymer lattice structures, indicating the need to explore other AM processes and materials [64].

Within this context, SDD offers a powerful approach to address the existing gaps in designing flexible lattice structures for AM. SDD enables virtual design, optimisation, and validation of lattice geometries while embedding AM-specific constraints, such as minimum feature size, build orientation, and process anisotropy, directly within the design loop. Although, SDD has been widely applied to design and optimise lattice structures [42, 68, 69], yet few studies combine it with DDfAM, especially when focusing on 3D-printed lattices [33, 70]. This represents a critical oversight, as manufacturing constraints and process-induced variations can significantly affect the mechanical performance of printed lattices [71, 72]. The issue becomes more pronounced when lattice features, such as strut size, approach the lower limits of manufacturability [73] which is a common scenario, as thinner struts are often used to enhance structural flexibility. Furthermore, research on SDD for flexible lattices has so far focused mostly on SLS-printed elastomeric materials [74], leaving the behaviour of stiffer bio-based polymers largely unexplored.

Building further on this, an SDD approach becomes particularly valuable for geometry-driven flexibility, where mechanical responses such as bending, buckling, or auxetic behaviour depend strongly on structural arrangements in lattices. Through numerical simulation, these deformation mechanisms can be predicted and refined before printing. As discussed in Section 1.1, experiments remain essential to accurately characterise the mechanical performance of 3D-printed parts. Therefore, an integrated simulation–experiment design loop can bridge the gap between virtual predictions and actual performance. By minimising such performance mismatches, the number of costly build-test iterations, material usage, and experimental validation efforts could be reduced. Over time, this iterative approach can evolve into a closed digital loop as shown in the Figure 1, where simulations guide design, experimental data validates performance, and feedback refines the model, evolving into a robust predictive approach capable of generalising across new lattice geometries and material systems.

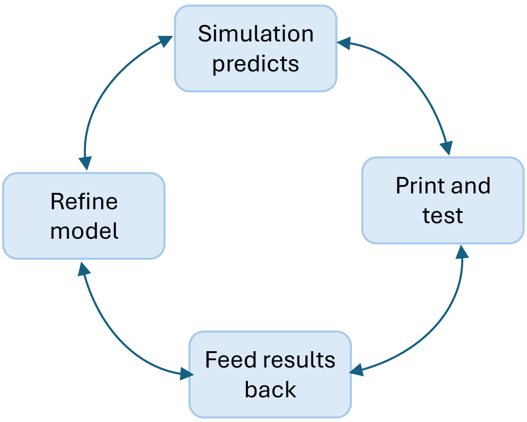


Figure 1: Closed loop simulation-driven design

Moreover, SDD supports multi-objective optimisation, enabling designers to balance flexibility, weight, energy absorption, printability, and sustainability, among others, which can be especially valuable when exploring the substitution of fossil-based materials with bio-based alternatives like PA11 in flexible lattice structures.

Despite the advantages of SDD and its increasing use in AM research, there is still a significant gap in how it can be systematically applied to design flexible lattice structures that combine both geometric and manufacturing considerations. This gap is particularly evident when trying to implement DDfAM within the design process, where both functionality and manufacturability need to be considered together.

Addressing the gap is central to this thesis, where the objective is to develop an SDD approach that connects lattice geometry, and manufacturing constraints along with material behaviour in order to create functional and manufacturable flexible lattice structures. By combining SDD with DDfAM, designers can precisely control structural behaviour through lattice geometry while accounting for AM-specific constraints, achieving desired mechanical performance with fewer costly trial-and-error iterations. This integrated approach not only optimises performance but also ensures manufacturability, resulting in higher-quality, more reliable, and easily manufacturable AM products. Moreover, lattice designs can fully leverage the unique capabilities of AM, such as tunable mechanical properties and individualisation. Furthermore, it enables multi-objective optimisation, balancing flexibility, strength, weight, and sustainability, while expanding the material palette to include stiff, bio-based polymers as alternatives to conventional fossil-based materials.

Industrial relevance and market perspective

Potential users for the proposed flexible lattice structures include manufacturers in aerospace, automotive, robotics, healthcare, and protective equipment sectors. These industries increasingly require components that are lightweight, high-performance, customisable, and structurally flexible which conventional manufacturing techniques often struggle to meet efficiently. The value proposition of this thesis work lies in combining performance, customisation, and sustainability, for instance, lightweight yet flexible lattice components such as airplane seatings can reduce fuel consumption and operational costs. Similarly, compliant lattices for soft actuators and grippers can improve precision and durability. In addition, custom-fit orthotics, prosthetics, and patient-specific implants or impact-absorbing structures in protective equipments represent areas where flexible lattices can act as bio-based alternatives to conventional foam solutions. Since these lattice structures are designed specifically for AM, improved part quality and functional integration are also expected. Moreover, from a circular economy perspective, geometry-driven flexible lattice structures make it possible to combine parts, reduce material use, and simplify assembly, leading to more resource-efficient products.

From a market perspective, conventional fossil-based materials remain dominant across industries that rely on flexible, load-bearing, or cushioning components, due to their established performance, availability, production infrastructure, and supply chains. Among these, PUR foam is one of the most widely used materials, with the global market projected to reach USD 73.6 billion by 2030, with the flexible foam segment showing particularly robust growth (~ USD 26 billion by 2030) [75]. In comparison, bio-based alternatives are growing rapidly, driven by sustainability trends, regulatory pressures, and demand for renewable yet high-performance materials. For instance, market forecasts suggest the bio-based foam market could exceed USD 1 billion by 2033 [76], reflecting increasing adoption across packaging, automotive, and furniture applications as suppliers seek eco-friendly alternatives to fossil-based PU foams.

As industries begin to respond to these market shifts, the economic viability of additively manufactured flexible lattice structures becomes increasingly relevant. Although AM and bio-based polymers may involve higher initial costs, monetary benefits arise from material savings, reduced assembly, faster prototyping cycles, customisation, longer lifespan, and regulatory/commercial advantages, making these solutions attractive to industrial customers seeking high-value performance alongside sustainability benefits.

1.3 Objective and research questions

DfAM is a broad research topic with varying focus areas including design, materials, processes, manufacturing, and post-processing. However, in this thesis, the presented research focuses only on part design within an engineering design process. Herein, *part design* refers specifically *to any changes in the form or geometry of a part without focusing on the process, machine, or material specific aspects of AM.* To address the research gap identified in Section 1.2, the overall research objective is presented in Figure 2.

Research Objective

> To advance the state of the art in dual design for additive manufacturing by enhancing knowledge on how to design flexible lattice structures that integrate both geometric and manufacturing considerations, incorporating a simulation-driven design approach.

Figure 2: Objective of the research presented in this thesis

Three research questions (RQs) were derived from the above research objective:

The first research question was formulated to be broad enough to explore the current state of DDfAM literature. First, it is essential to understand the areas where DDfAM research is concentrated and then identify the literature gaps that may exist, particularly focusing on lattice structures. Secondly, it is necessary to investigate the existing design strategies[2] that are currently adopted for employing DDfAM. 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 DDfAM, particularly concerning lattice structures.

Thus, 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 through these interconnections. These issues were used to formulate the first research question:

- *RQ 1:* What are the key research areas in the field of dual design for additive manufacturing related to the design of lattice structures, and how do the existing strategies contribute to their design?

Further, as mentioned previously, the concept of DDfAM 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 geometry-specific parameters that affect the part design, and the manufacturing constraints that constrain the design. Since structural flexibility is the primary objective guiding this work, it is essential to determine which design parameters and manufacturing constraints affect it alongside other relevant considerations, including manufacturability and material robustness.

Apart from identifying the 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 material failures, etc., and clarifying the impact these interactions have on the flexibility of the intended lattice structures.

[2] In this thesis, the term ‘design strategies’ is used to collectively represent design methodologies, tools, and methods [77], rules, and guidelines [9].

Without such clarifications, it will be difficult to attain the desired flexibility in these structures. To understand these issues, the second research question was formulated, as presented below:

- ❖ *RQ 2:* What influencing factors may be considered when designing flexible lattice structures for additive manufacturing?

Finally, identifying the influencing factors and understanding how they interact can provide valuable insights for designing flexible lattice structures. However, incorporating these factors and their interactions using computational approaches such as SDD is crucial for optimising designs, achieving the desired mechanical performance and ensuring manufacturability. SDD approaches employing FE-based numerical modelling have been commonly used in engineering design processes; hence, much work has been done in such a context, however, their utilisation in complex design problems, especially concerning flexible lattice structures with an emphasis on DDfAM in the design process, is under-explored. Furthermore, to enable faster design iterations, these influencing factors and their interactions need to be efficiently integrated within the design process. When well integrated, SDD can be applied to bridge design and manufacturability, enabling functional flexible lattice structures in real-world scenarios, that are specifically designed for AM. These issues are formulated into the third research question, as presented below:

- ❖ *RQ 3:* How can a simulation-driven design approach be developed and applied to integrate influencing factors in the design of flexible lattice structures for additive manufacturing?

1.4 Research focus and delimitations

The presented research lies at the intersection of DfAM, SDD, and lattice structures, as illustrated in Figure 3.

Within the domain of SDD, FE-based numerical modelling within the engineering design process was emphasised, specifically focusing on the detail design phases, with particular emphasis on its role in informing design decisions while validating performance; within DfAM, dual DfAM, i.e., DDfAM has been the main focus, adopted for part design within an engineering design process, without focusing on materials, machines and processes; and within lattice structures, uniform strut-based lattice structures were explored. Together, the intersection of these focus areas aims towards fulfilling the research objective outlined in this thesis.

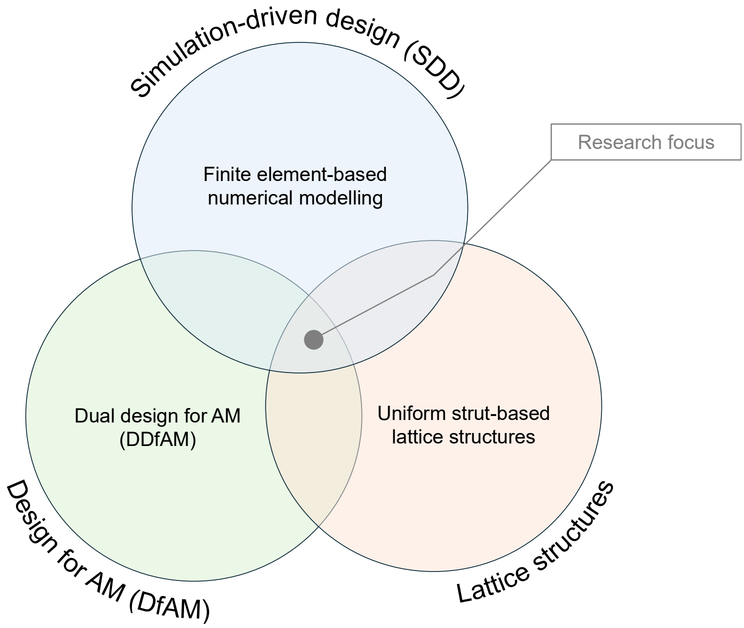


Figure 3: Illustration of the research focus

Among the several AM processes available, this research focuses only on the polymer L-PBF process, more specifically SLS. The process selection was primarily inspired by the availability of in-house printers, and compatibility with the chosen material.

The motivation for this research was to enable geometry-driven flexibility without relying on the inherent softness of base materials, while also catering to the growing industrial interest in bio-based polymers for improved environmental sustainability. In line with this strategy, a bio-based polymer powder, PA 1101, developed by EOS GmbH [58] specifically for SLS printing, was chosen. The STEPS project [57], which supports the sustainable transition in the plastics industry by developing biopolymers, further reinforced the material choice. By focusing on such sustainable materials, the research aligns with broader efforts to reduce reliance on traditional fossil-based polymers while still achieving the desired mechanical and functional performance. Although there are various bio-based materials available commercially, those that are available for 3DP at a reasonable cost are limited. Additionally, since there is scalability issues associated with in-house-produced bio-based 3DP compatible materials by STEPS project partners at the department of Chemical Engineering, LTH, the chosen material PA 1101 turned out to be the most suitable option.

Although other AM processes such as FDM or Stereolithography (SLA) are frequently used for polymer 3D printing, they are generally limited in terms of consistency and mechanical properties compared to the relatively isotropic properties achieved with SLS. As a result, SLS was selected for printing PA 1101, which is a material well-suited for the process. Additionally, the printer process settings, and the machine operator were kept the same to ensure consistent sample quality suitable for experimental investigations.

Lattice structures were chosen for this research because of 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 with topologies commonly used in existing literature being the starting point. 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 geometric modelling tools. To achieve the research goal of structural flexibility, thin strut-based geometries near the lower limits of manufacturability for the SLS process are explored, where process-induced variations are more pronounced. This further reinforces the DDfAM focus on this research.

The work focuses on lab-scale specimens and extends the investigation to a larger, real-world component through prototyping, but it does not include any large-scale experimental campaigns. As a result, numerical simulations are primarily calibrated using data from these lab tests, with testing of full-scale industrial structures considered beyond scope. Moreover, SDD was adopted in this research due to its broad applicability in virtually validating and iterating part designs. Further, DDfAM might have competing objectives (e.g., mechanical performance vs. manufacturability) wherein an SDD approach can support in evaluating such design decisions and allow for efficient design optimisation. The structural behaviour studied is mainly limited to structural flexibility under compression, emphasising static elastic responses; cases involving plasticity, dynamic loading, or fatigue are not included in the scope. Additionally, the focus lies on the integration of DDfAM within the engineering design process, while full-scale product development, including lifecycle analysis and cost-benefit analysis, remain outside the scope.

The application area in focus within the STEPS project is the furniture industry, particularly a Swedish furniture company [78] that has shown interest in investigating flexible lattice structures for upholstery design. However, the research presented in this thesis is not restricted by the cases within this application area. Rather, the upholstery application in STEPS project has served as motivation for this research.

1.5 Thesis outline

This dissertation is divided into six chapters.

Chapter 1 introduces the topic, problem statement, research objective and research questions, along with related delimitations.

Chapter 2 describes the frame of reference for the presented research.

Chapter 3 outlines the research methodology adopted to conduct the intended research.

Chapter 4 summarises the results in the appended papers.

Chapter 5 discusses the research findings and presents the main research conclusions.

Chapter 6 presents the research contributions and limitations, including suggestions for future work.

2 Frame of reference

This chapter outlines the frame of reference for the research[3] presented in this thesis. An overview of the key concepts related to this research is discussed along with some insights into the related existing literature.

2.1 Engineering Design

Engineering design is a systematic step-by-step process of defining a product to meet the desired needs with realistic constraints, involving four main phases [79]. The four phases, as illustrated in Figure 5 include the planning phase (involves information specification), conceptual design phase (involves conceptualisation or solution specification), embodiment design phase (involves layout specification), and detail design phase (involves production specification).

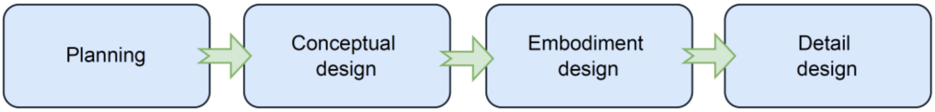


Figure 4: Engineering design process; adapted from Pahl, et al. [79]

According to Pahl, et al. [79], 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 further 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 [80]. Today, different phases of the engineering design process are largely supported by computer-aided methods, e.g., computer-aided design (CAD)

[3] Partly based on Dash (2023) *Design of flexible lattice structures. A design for additive manufacturing perspective* (Licentiate Thesis), Lund University, Lund, Sweden

for geometric modelling, computer aided engineering (CAE) for design evaluation, and computer-aided manufacturing (CAM) for manufacturing process-specific preparation and simulation [80], easing the design process for advanced technologies such as additive manufacturing.

The engineering design process typically strives to deliver high-quality, high-performance products requiring several key activities to be carried out at each phase [79, 80]. Effectively managing these activities necessitates iterative and flexible approaches to address inherent complexities and the demands of rapid innovation. Some of these needs are addressed through concurrent engineering, which enables parallel task execution and cross-functional collaboration [81], or agile methods, which promote adaptability through incremental development and continuous feedback [82]. Unlike traditional stage-gate models that follow a linear, sequential structure [80], these modern approaches support faster, more responsive design cycles better suited to the current dynamic engineering environments.

2.1.1 Design for X

Design for X (DfX) is a generic term for design strategies adopted to improve product design and the design process from a specific perspective, represented by 'X' [83]. For instance, design for quality (DfQ) focuses on ensuring product quality as the primary objective, while design for environment (DfE) emphasises minimising environmental impacts throughout the product lifecycle [80, 84]. In DfX, addressing the chosen focus early in the design process is essential for making well-informed and effective design decisions [79, 85]. DfX, therefore, forms a subset of design theory and methodology (DTM), which emphasises the study and organisation of design activities and processes rather than solely on the final 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" [85, p. 544]*

2.1.2 Design manufacturing and assembly

Design for Manufacturing and Assembly (DfMA) is a widely adopted strategy within the broader concept of DfX. Design for Manufacturing (DfM) and Design for Assembly (DfA) are often combined under the umbrella of DfMA [86, 87]. Within product design, DfMA seeks to simplify manufacturing and assembly processes to reduce associated costs and challenges. Therefore, it is important that the designs (and designers) account for the opportunities and restrictions presented by manufacturing processes, thereby reducing production time and costs, minimising defects and failures, and avoiding costly, low-performance outcomes [80].

2.2 Additive Manufacturing

In recent years, advances in technologies have made manufacturing processes more digital, flexible, and efficient [2]. Additive manufacturing (AM), or 3DP, is a transformative technology that additively creates 3D physical objects from a digital 3D model by depositing material layer-by-layer, as opposed to conventional subtractive processes such as turning, milling, and shaping. A wide variety of materials, including metals, ceramics, polymers, composites, and hybrids, can be fabricated with AM.

2.2.1 AM workflow and process classifications

The general workflow of AM is illustrated in Figure 5. In this process, the object data is captured from 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 digitally 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 manufactured [6].

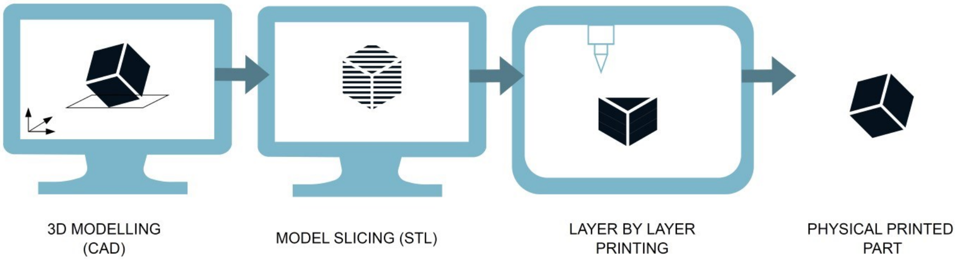


Figure 5: A general additive manufacturing workflow

The American Society for Testing and Materials [5] has categorised AM into seven different categories: powder bed fusion (PBF), material extrusion (MEX), material jetting (MJT), binder jetting (BJT), directed energy deposition (DED), VAT photopolymerisation (VPP), and sheet lamination (SHL). These AM processes mainly differ in how the printing material is deposited to form a 3D object. In MEX, material is extruded through a nozzle and selectively deposited layer by layer, following the part geometry. In MJT, which is similar to inkjet printing, droplets of material such as photopolymer resin, is selectively deposited. BJT is similar in approach but instead uses a liquid binding agent to join powder particles together. In DED, material, usually in the form of powder or wire, is deposited while a focused thermal energy source melts it, allowing the material to fuse upon deposition. Finally, in SHL, sheets of material are bonded and cut according to the desired geometry to build the final 3D part [5, 6].

Among the various AM processes, laser PBF (L-PBF) stands out due to its ability to produce highly complex and high-precision parts, particularly with polymers and metals [88]. 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 [74]. The SLS process has been illustrated in Figure 6.

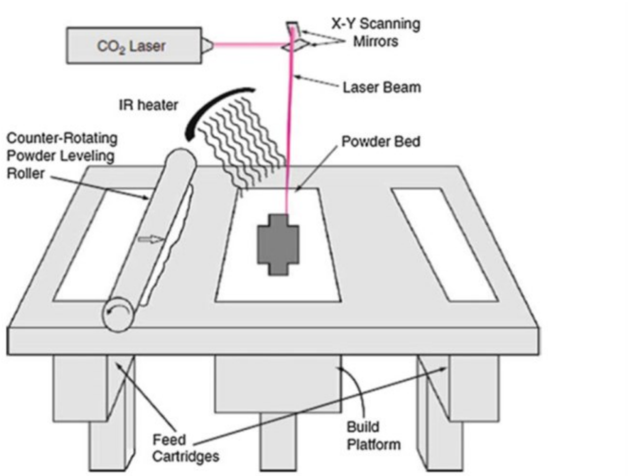


Figure 6: Illustration of the SLS process. Courtesy: Gibson, et al. [6]

2.2.2 Capabilities and constraints of AM

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 [6]. Nevertheless, similar to any other manufacturing technology, AM has its own set of constraints. According to Deloitte [89], 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., support structure requirements, 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). Certification and regulatory requirements add further complexity for industrial adoption [14, 90]. Although several of these constraints have not been addressed completely, there has been ongoing research attempting to minimise them [91, 92].

2.2.3 Identifying Suitable Parts for AM

To harness the design potential of AM, it is necessary to identify parts in a product where the advantages of AM create the most value to the customers [93]. Whether a part can benefit from these advantages, can serve as a useful criterion for identifying suitable ones to fully leverage the geometric freedom offered by AM. A detailed explanation of other criteria, along with different examples of their implementation in practical scenarios, is presented in Klahn, et al. [94]. Additional factors that influence the suitability of parts for AM include part volume, expected cost, advantage over other manufacturing techniques, material compatibility, mechanical requirements, and desired surface finish [95]. Therefore, selecting a part for AM is difficult and entails a trade-off between different design and manufacturing parameters [6].

2.3 Design for Additive Manufacturing

The evolution of AM has introduced unique capabilities that have significantly expanded design freedom, allowing designers to overcome many of the limitations associated with traditional manufacturing processes. For example, injection molding process imposes design constraints like the need for draft angles, the avoidance of undercuts or re-entrant features, and the presence of weld lines [96], which can be overcome through AM technologies. Additionally, challenges in manufacturing complex geometries such as hollow interiors or intricate internal channels can be effectively addressed through AM [97].

However, AM introduces a distinct set of constraints that differ from those of traditional processes, such as those related to layer-wise fabrication, thermal distortion, surface finish, and build orientation, among others. As a result, traditional DfM methodologies require adaptation to suit the specific characteristics of AM. This has led to the evolution of design for additive manufacturing (DfAM) [10], which builds upon the foundational principles of DfM but is tailored to exploit the unique opportunities and address the specific limitations inherent to AM technologies [96].

In this context, the interplay between machine, material, and geometry becomes particularly critical. The inherent complexity and interdependence among these three dimensions govern not only the manufacturability but also the mechanical performance, dimensional accuracy, and overall quality of AM-ed parts. Therefore, a process-specific understanding of design implications is essential to fully leverage AM capabilities and ensure reliable part outcomes [98].

2.3.1 Theoretical foundations and classifications in DfAM

In recent years, the rapidly growing field of DfAM has witnessed increasing involvement from the scientific community, as evidenced by the significant growth in research publications during the past few decades [9, 13].

Despite this growing attention, many component design processes still adopt AM post-design, rather than designing with AM in mind [99]. As a result, parts are often developed without accounting for AM-specific requirements, for instance, when print orientation is not taken into account during the design phase, excessive sacrificial support structures may be required to ensure buildability [100]. Such inefficiencies increase resource consumption and can compromise product quality, highlighting the need to reframe engineering design processes to fully exploit the benefits of AM while addressing the challenges that come with it. This, in turn, calls for design strategies that support DfAM and explicitly incorporate AM-specific constraints throughout the design process.

According to Rosen [98], 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 [6]. However, despite the attempt at establishing a general definition, DfAM has encountered diverse interpretations within the research community.

While some researchers connect DfAM with exploiting design capabilities or constraints associated with AM, others emphasise material-process relationships as DfAM, and some view it as a set of design strategies to assist designers in creating products tailored for AM [13, 87]. To bring clarity to this fragmented landscape, a meta-review paper by Lopez Taborda, et al. [12] synthesised the contributions of various studies. Their work helped cater both the converging and diverging perspectives within the field, though it is restricted to a methodological perspective. This highlights the ongoing need for a unified understanding of DfAM that accommodates its multidisciplinary nature.

Laverne, et al. [11] catergorised DfAM into three types, as illustrated in Figure 7: *Opportunistic DfAM*, which encourages designers to fully exploit the unique capabilities of AM technologies (e.g., complex geometries, mass customisation);

Restrictive DfAM, which emphasises the need to design within the constraints imposed by AM materials, machines, and processes (e.g., support structures, print orientation, thermal distortion); and *Dual DfAM (*referred as *DDfAM* in this thesis*)*, which combines both the opportunistic and restrictive DfAM to take advantage of the full potential of AM.

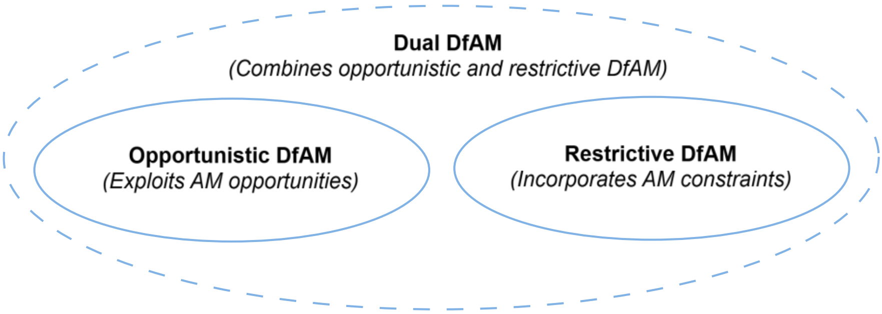


Figure 7: Simplified representation of the three categories of DfAM, adapted from Laverne, et al. [11]

Extending the above three types, Kumke, et al. [87] distinguishes: *'DfAM in strict sense',* focused on design rules and guidelines to utilise AM design potentials and navigate AM-specific challenges, and *'DfAM in broad sense'* which additionally encompasses upstream and downstream activities such as part and process selection, and manufacturability analysis, among others. Extending the classification proposed by Kumke, et al. [87], a bibliometric analysis by Obi, et al. [13] classified the existing DfAM knowledge into: DfAM potentials; DfAM limitations; DfAM specifics such as rules, guidelines; and AM process parameters. Pradel, et al. [9] further developed the foundation laid by Kumke, et al. [87] by mapping DfAM knowledge across all phases of the design process, incorporating not only the core engineering phases but also materials, manufacturing, and post-processing considerations, although their perspective leans more toward product and industrial design than engineering design per se. These studies collectively underline the need for a holistic, system-level view of the field and also emphasise the importance of considering both opportunities and constraints in AM, aligning closely with the concept of DDfAM.

In essence, these studies converge on the importance of DDfAM, highlighting the importance for designers to adopt this perspective in order to fully leverage the creative potential of AM while remaining mindful of its specific constraints [9, 11, 87]. For the DfAM classifications in these studies to be effective, the interrelations between design considerations must be understood and operationalised, enabling designers to actively integrate them throughout the process. This shows the need for DfAM to evolve into a practical lens through which designers can perform informed decision-making from ideation to production, allowing them to effectively harness specific complexities when designing for AM.

2.3.2 Design strategies supporting DfAM

A variety of design strategies[4], including methodologies, tools, methods, rules, and guidelines, have been developed to support design for AM [9, 88]. From a DTM perspective, Yang and Zhao [96] critically reviewed how AM influences conventional DTM practices. They proposed design strategies across three key areas: (a) AM-specific design guidelines that help designers explore unique opportunities; (b) adaptations of traditional DTM strategies to align with AM-specific opportunities; and (c) integrated design strategies that combine functional requirements with manufacturing constraints in part design. Their findings suggest that design strategies that can support the better adoption of DfAM, especially DDfAM, can empower designers to exploit the capabilities of AM while effectively managing design uncertainties introduced by the process.

When DfAM is concerned, different design strategies have been implemented across different phases of the engineering design process, each serving different purposes. Among these strategies, those focused on exploiting AM opportunities include inspirational stimuli such as design heuristics in the form of object/cards-based tools [101, 102] and curated inspirational objects [103], which are used to enhance creativity in early phases of design. If AM is not the primary manufacturing process and is rather utilised for prototyping or short run part production, the manufacturability of the parts can be hampered by design fixation (i.e., psychological inertia to switch manufacturing processes) resulting in difficult-to-manufacture designs [104]. Similarly, while DfAM opens up opportunities for creative solutions with high complexity [105], it may also result in difficult-to-manufacture and/or expensive designs [106]. Therefore, it is important to account for design fixation during the early design phases.

To balance creativity with manufacturability, computational design strategies are increasingly employed in later phases of the design process. Widely adopted CAE-based design strategies include topology optimisation (TO) and size optimisation, which not only exploit the design freedom in AM but are increasingly used to incorporate manufacturing constraints by imposing geometric limits on the design space [107, 108]. In addition, some studies that have explored design strategies that simultaneously consider both the opportunities and constraints of AM as documented in existing reviews [9, 13, 96, 109], thereby supporting a DDfAM perspective. Paper A appended in this thesis, elaborates on the range of existing design strategies that support this perspective.

---

[4] See Note 2.

Collectively, the existing DfAM-oriented design strategies support designers in systematically reaching their design goals. These include strategies for generative design, such as, topology optimisation [110]; the design of multi-scale structures, like lattices[111]; multi-material design [50]; mass customisation[112]; and part consolidation [113], along with other strategies that facilitate AM-enabled designs. However, these existing design strategies supporting DfAM are often limited in scope, typically tailored to specific design stages and/or limited to certain AM processes [12, 87]. Additionally, they generally 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 [12].

Design strategies vary in terms of their specificity to AM processes. While some of the design strategies are process-agnostic [9, 13, 96, 108], others are tailored to specific AM technologies, such as material extrusion processes [114, 115]. Process-specific design strategies often focus on aspects such as part geometry (e.g., managing overhangs), quality (e.g., surface roughness), material properties (e.g., anisotropy, mechanical performance), and sustainability considerations, including energy consumption and impact on producer-consumer-community connections, which is an area that remains relatively underexplored but gaining attention [12].

Existing computer-based design strategies have enabled various levels of design automation in DfAM, providing timely guidance during the design process. These strategies support geometric modelling, TO, FE simulations, process simulation, and design preparation, including pre-printing setup and slicing; often facilitated by commercially available software [107, 116]. For instance, they support critical design tasks such as data management, integrated optimisation, and trade-offs between conflicting objectives such as balancing support structures, manufacturability, and manufacturing cost [107, 108]. Despite their potential, these strategies still have limitations in how comprehensively they support DfAM throughout the design process [27, 96]

Emerging strategies have further incorporated machine learning (ML) for part design, including exploration of design space, optimisation of print orientation, and predicting geometric deviations in printed parts [117]. However, these developments have not completely eliminated the need for manual intervention. Designers still engage in non-automated tasks such as design modifications and result interpretation, which require multidisciplinary expertise and cross-domain software fluency [108].

Design strategies supporting DfAM increasingly consider sustainability and cost performance, though both remain underexplored. Integrating environmental aspects into DfAM can guide designers in assessing lifecycle impacts alongside functional performance [118, 119]. Similarly, incorporating cost-related factors, such as machine, manufacturing, and maintenance costs, can support in informed decision-making when adopting DfAM [27, 120].

In summary, design strategies in DfAM span a broad spectrum, ranging from creative aids and process-specific guidelines to simulation-driven design, optimisation and automation strategies. While these strategies have significantly advanced the integration of AM in engineering design processes, they are often fragmented, vary in their levels of process dependence, and despite design automation, often requires substantial manual effort and expertise. Unified, adaptable, and intelligent design strategies that can holistically support designers in navigating the complexities of DfAM across varying contexts and AM technologies are therefore necessary.

2.4 Design of Lattice structures

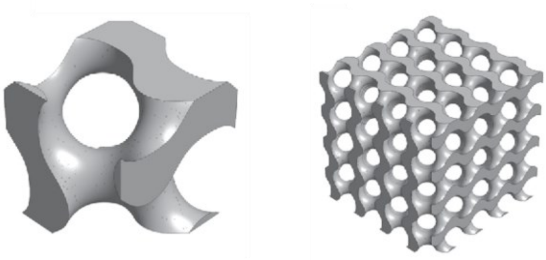
Lattice structures represent one of the prime examples where design strategies supporting DfAM can be applied, demonstrating how designers can integrate design freedom, structural performance, and process constraints in complex AM parts. They form a subset of cellular structures, which consist of networks of connected trusses (i.e., struts) or plates, that are either stochastic, such as foams or voronoi patterns, or non-stochastic in nature, such as lattice structures [121]. These hollow structures consist of interconnected, periodically arranged 3D building blocks called unit cells [121, 122], making them particularly well-suited to AM, which enables designers to create complex geometries while maximising design freedom [123].

2.4.1 Classification and functional characteristics of lattice structures

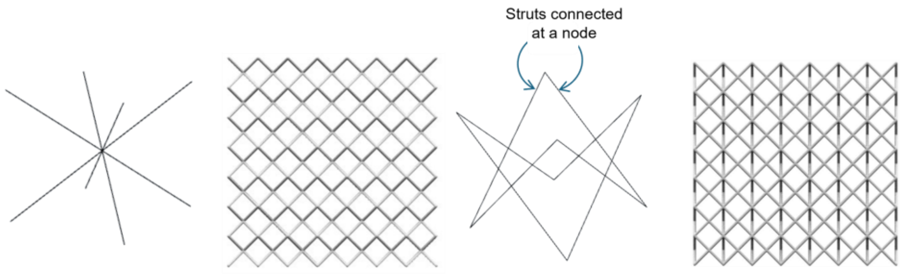
Lattice structures can be broadly classified into two main categories: surface-based and strut-based. Surface-based lattice structures are defined by unit cells generated from the isosurfaces of mathematical functions. A well-known example of this type includes triply periodic minimal surface (TPMS) lattices [124], as illustrated in Figure 8a. Strut-based lattice structures comprise of unit cells with interconnected struts and nodes, where struts serve as links and nodes act as joints where the struts connect [125]. Common examples include body-centered cubic (BCC) and face-centered cubic lattices, also shown in Figure 8b. This dissertation focuses primarily on strut-based lattices, which have been extensively studied in the literature [64, 126].

The mechanical properties of natural materials are often limited in range, for instance, most exhibit a positive Poisson's ratio. This inherent restriction can constrain the design space for advanced engineering applications. To overcome these limitations, researchers have developed metamaterials, which are engineered materials with mechanical behaviour governed more by their structural architecture rather than the properties of the bulk material they are built from [127, 128].

Examples of such metamaterials include chiral/anti-chirals, auxetic, and origami- and kirigami- inspired structures, among others [128]. Some of these are presented in Figure 9.



(a)



(b)

Figure 8: Examples of lattice structures with their constituent unit cells a) sheet-based TPMS lattice structures, Courtesy: Maskery, et al. [124] b) strut-based lattice structures showing BCC (left), FCC (right) structures

Lattice structures form a key subclass of metamaterials, which derive their functionality primarily from the geometry of their repeating unit cells. Different types of lattice structures studied in the current literature include functionally graded lattice structures (FGLS), where the density of the designed structure is optimally distributed [129], conformal lattice structures (CLS), where unit cells with different sizes and geometry adapt and conform to the external boundary of the 3D model [38], and multi-material lattices [35], among others.

Lattice structures can be precisely engineered to behave as monolithic materials with unique mechanical properties [47]. Due to their unique properties, they have seen widespread applications in biomedical, aerospace, and automotive fields [64], such as for lightweighting due to their high strength-to-weight ratio [64, 122, 126], for heat exchange due to their high surface area-to-volume ratio [126, 130], and for energy absorption due to their ability to undergo large deformation at a relatively low stress level [64, 126, 130], among others. Furthermore, these structures can be designed to perform multiple functions simultaneously within a single component, thus, exhibiting great functional flexibility [131].

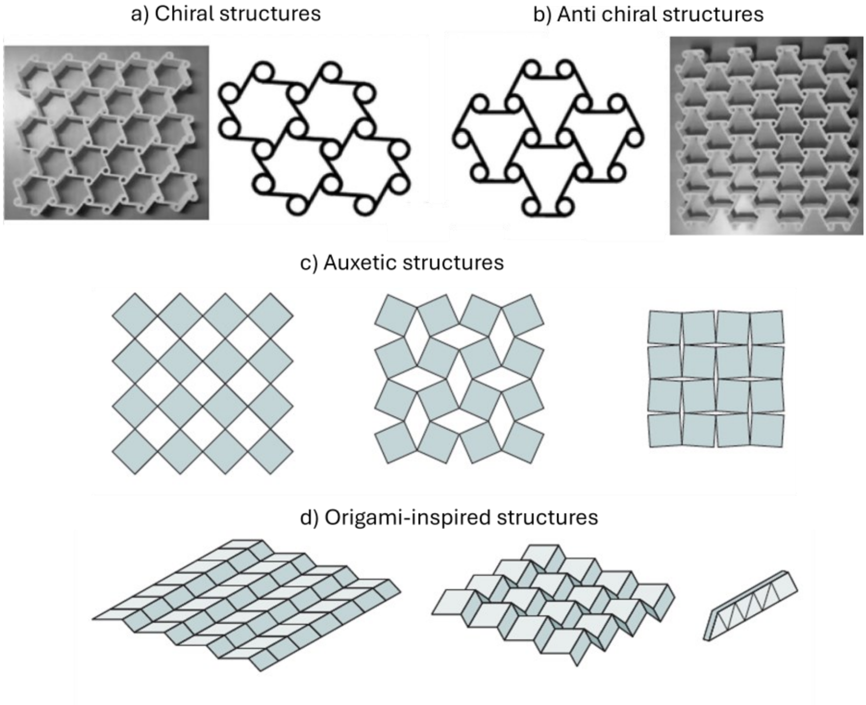


Figure 9: Examples of mechanical metamaterials, (a-b) Chiral and Anti chiral structures, Courtesy: Yu, et al. [128]; (c-d) Auxetic and Origami-inspired structures, Courtesy: Bertoldi, et al. [48]

These unique properties are largely governed by the mechanical performance of lattice structures, which can be tailored by carefully engineering geometry-specific factors, 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), periodicity, unit cell size and topology, as well as strut thickness [131, 132]. This performance is further influenced by material properties, loading direction, and manufacturing processes [38]. Understanding the influence of these factors and their interplay is therefore essential for the design and implementation of lattice structures for advanced engineering applications.

2.4.2 Modelling, simulation, and optimisation strategies

The properties of lattice structures are largely determined by the design of their repeating unit cells. As a result, CAE-based strategies for designing complex lattices have advanced significantly, focusing mainly on the design and optimisation of single unit cells [133]. These strategies can be grouped into three main categories: (a) primitive-based strategies, which use Boolean operations on basic shapes like cubes, spheres, or cylinders to form unit cells [131]; (b) implicit surface strategies, where unit cells are defined using mathematical equations to create smooth, continuous surfaces [131]; and (c) topology optimisation-based strategies, which generate unit cell geometry by optimally placing material and voids to achieve desired performance [134].

Building on these CAE strategies, parametric modelling provides a practical route for designing larger, complex lattice structures by replacing solid regions with truss- or strut-based geometries [135]. Geometrical modelling of lattice structures commonly employs, for example, boundary representation (BRep) and volume representation (VRep), among others; however, the capabilities in commercial CAD software are still limited, with most of them adopting BRep approaches owing to the ease of implementation, ability to handle complexities (e.g., fillets), and lower computational demands [126]. Some of the available CAD software for geometric modelling of lattice structures includes Rhinoceros 3D, Autodesk Fusion, and nTopology.

FEA has become integral to the design and optimisation of lattice structures, enabling accurate prediction and validation of mechanical performance. It is commonly used to incorporate manufacturing constraints during design [38, 136], optimise lattice geometry for enhanced performance [137-139], and evaluate material properties such as stiffness and strength [34, 35, 140]. By simulating stress-strain behaviour under various loading conditions, FEA facilitates the refinement of unit cell configurations and lattice architectures. Moreover, recent studies have incorporated FEA into iterative and automated design workflows, enabling performance feedback and continuous optimisation [33, 141]. Together, these FEA-based strategies serve as an important category of design strategies that enable predictive analysis and decision-making concerning the design of lattice structures; Paper A appended in this thesis has more details on scope and limitations within this focus area.

Gradient-based TO is widely used in lattice structure design to tailor material distribution and infill patterns at micro- and mesoscales, accounting for process-specific anisotropy [34, 137, 142]. Elimination of support structures coupled with enhancement of thermal and mechanical performance is made possible using TO as well [35]. Similarly, multi-scale structural optimisation strategies have simultaneously refined unit cell geometry and lattice structures design while addressing AM constraints to ensure manufacturability and reduce post-processing

[143-145], thus, aiming for the design of high-performance, manufacturable lattice structures. These optimisation strategies have been further discussed in Paper A appended in this thesis.

2.4.3 Lattice structures as flexible structures

As stated by Howell [23], *"if something bends to do what it is meant to do, then it is compliant"*. Unlike traditional systems that rely on rigid joints like in door hinges or sliding joints to enable motion, it is also possible to achieve movement through structural flexibility. Such flexibility involves bending of the structure, much like what we observe in nature, such as bee wings flapping, elephant trunks curling, or seaweed swaying with ocean currents. A basic example in everyday life is the elastic band, which relies on its flexibility to stretch and hold things together.

Engineered metamaterials such as origami and kirigami structures have shown how flexibility can be designed into materials through strategic folding or cutting. For instance, origami tessellations enable controlled curvature and programmable motion [146], while kirigami enables graphene-based flexible electronics by introducing cuts into a stiff material [147]. These concepts of geometry-driven structural flexibility have inspired the design of another category of metamaterials, i.e., lattice structures, which have proven to be useful in many applications requiring structural flexibility. For example, lattice-based wings have been used in the design of unmanned aerial vehicles [148], and shape-morphing lattices have been designed for adaptability in structures [51]. These examples demonstrate how structural flexibility can reduce the number of parts, potentially avoiding bearings or fasteners, enabling movement without relying primarily on structural stiffness.

Flexible structures offer several practical advantages. They are generally lighter, since they avoid heavy rigid components, and experience less wear and backlash, which can increase their durability and performance. They provide scope for the integration of functions into fewer parts, potentially reducing cost, assembly, and inventory requirements. For these reasons, there has been ongoing interest in their design, with researchers developing various solutions like flexible structures built with spring and beam arrangements [142] and highly stretchable, accordion-like forms [149]. Within this context, lattice structures designed for flexibility bring even more to the table. They allow multi-state behaviour, where the same structure can adapt to different functions depending on the load, such as switching from a packaged to a deployed state; multi-functionality, such as offering different configurations depending on different functionality requirements; and integrated functionality, which allows fewer parts to do more.

The relevance of flexible lattice structures has become even more pronounced in the context of emerging sustainability goals. For instance, within the STEPS project [57], previously presented in Section 1.4, there is a strong focus on using bio-based polymers to serve as sustainable alternatives to conventional fossil-based materials like PUR foam, typically used in applications such as furniture upholstery. However, replicating the foam-like functionality of PUR using bio-based polymers that are often stiffer by nature, remains a challenge. One way to measure this flexibility is through Young's modulus (E). For bulk materials, E is fixed, but in lattice structures, which act as metamaterials, the effective E can be tailored by adjusting their geometry. In this thesis, the term *flexible lattice structures* refer specifically to *lattice structures that exhibit an effective Young's modulus comparable to that of elastomeric foams, thereby enabling foam-like functionality using alternative, often stiffer, base materials.*

2.4.4 DfAM of lattice structures

Alternative manufacturing techniques such as water jet cutting, investment casting [150], and electro-discharge machining [151] have been used to manufacture lattice structures, particularly at large scales. However, they involve complex setups, high material waste, limited geometric precision [133], and often require additional assembly or bonding. Moreover, these methods significantly restrict the range of achievable lattice architectures [131].

With the rapid advancement of AM technologies, it has become much easier to design and fabricate lattice structures with tailored functional characteristics [64, 126]. Unlike traditional techniques, AM allows for greater design freedom, enabling the creation of intricate geometries that were previously difficult or impossible to produce. However, it also brings new design considerations arising from the unique constraints of AM. Some of these include machine and material limits, such as build volume, print resolution, material compatibility, anisotropy, and porosity [90, 152]; process constraints, related to support structures and print orientation [107, 152]; post processing requirements related to support removal and machining [90, 107]; and quality control issues, such as geometrical accuracy, surface roughness, and internal defects [14, 152]. Existing design strategies such as constrained topology optimisation, process simulation and optimisation, and multi-disciplinary strategies [29, 116, 153, 154] provide ways to address these constraints while also exploiting design freedoms, but systematically integrating multiple constraints and their interactions remain challenging.

Therefore, it is essential to consider both the opportunities and constraints of AM simultaneously in a design process [11]. This integrated perspective forms the core of DDfAM. When it comes to lattice structures, this involves aligning performance goals with suitable materials, lattice geometry, and the AM process itself. The *"performance-property-structure-process"* framework presented in [155] is particularly useful in this context, helping designers connect mechanical performance to design and manufacturing choices.

The mechanical performance of lattice structures is highly influenced by geometric parameters such as topology, unit cell size, and strut thickness, whose manufacturability across different configurations has been explored by Kummert, et al. [74]. These parameters offer designers, the freedom to tune the desired mechanical performance related to stiffness, energy absorption, or flexibility; although the base material properties also influence the performance [130, 132]. However, this performance is limited by the AM-specific design considerations [156], relating to minimum printable feature size, printing resolution limits, among others. For example, how fine a strut can be printed or where support structures are needed, can influence both the manufacturability and final performance of the lattice [131]. As a result, designing lattice structures for AM depends on how geometry, material, and process work together, each choice affecting how the structure will perform.

There has been significant increase in studies examining lattice structures, including their geometry [132] and mechanical properties, through both numerical and experimental investigations [64-66, 157-160]. These studies, however, rarely discuss the adoption of DDfAM for the design of lattice structures, and tend to focus on single influencing parameters at a time rather than considering the geometry, material and process trade-offs together. A dual perspective not only improves manufacturability [29] and encourages broader adoption by practitioners [161] but also promotes design innovation [11].

As reflected in the literature discussed above, while existing studies have investigated the compressive or load-bearing behaviour of lattice structures, there is relatively limited work on designing for flexibility, i.e., flexibility as the primary goal [20, 21, 70]. Moreover, even studies addressing flexibility often overlook key performance determinants such as printing orientation by considering them during print preparation rather than integrating them into the design process [67].

Current research efforts also predominantly focus either on PBF-based metal or ME-based polymer lattice structures [64]. There is limited exploration of other AM technologies, like SLS, or sustainable materials, like bio-based polymers. Designing for flexibility remains underexplored, which is particularly relevant in the context of this thesis that focuses on lattice structures, designed for flexibility, thus, aiming for *flexible lattice structures*. In such cases, governing materials, geometric parameters, and the process-specific design considerations are required to be re-evaluated with flexibility as the primary performance metric.

2.5 Simulation-driven design

Simulation-driven design or SDD 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”* [162].

2.5.1 Role and importance of SDD in Engineering design

Early work in engineering design and CAE established the value of simulations for exploring design alternatives and assessing performance before physical prototyping, making simulation a key complement to other established design practices [79, 163]. Foundational contributions in structural and multi-disciplinary optimisation further demonstrated how numerical models and analysis tools support better and more informed decision-making, especially for complex engineering problems [164, 165]. These early insights laid the groundwork for viewing simulation not only as a verification tool but as a driver of the design process itself. While SDD offers powerful capabilities for exploring and evaluating design alternatives, it continues to face practical challenges, including uncertainties in model predictions [166], the computational demands of high-fidelity simulations [167], and the need for specialised expertise to implement and interpret simulation results effectively [168]. Even so, SDD has become increasingly important in areas such as DfAM, where simulations help predict structural performance, assess manufacturability, and guide decisions in handling geometric and process-related complexities, further elaborated in the following sections.

2.5.2 SDD supporting DDfAM

Simulation-driven design has become a fundamental approach in DfAM, enabling engineers to shift from trial-and-error prototyping to computational prediction and optimisation [33]. The core idea is to use numerical models early in the design process to evaluate how a component will perform mechanically and how it will behave during fabrication [169]. Topology optimisation is the most widely used SDD technique in this context, where algorithms determine the optimal distribution of material within a design space based on loading conditions and performance targets [134, 170]. For AM, these optimisation algorithms are extended to include manufacturing constraints, such as process-induced adhesion forces [171] and deformation [172-174] with overheating [36], powder entrapment [140, 175], residual stress and warpage [176], and dimensional inaccuracies [33], reflecting a DDfAM approach that balances design freedom and process constraints. Recent advances integrate machine learning to accelerate these computations and to make the design process more aware of real-world manufacturing constraints, such as defect formation tendencies or surface finish trade-offs in metal and polymer systems [177, 178].

Beyond optimising geometry for structural performance, SDD also encompasses process simulations to predict what happens inside the AM machine during the printing process. Thermo-mechanical FE models simulate the layer-by-layer heating and cooling cycles, capturing thermal gradients, residual stresses, and part distortion that can compromise dimensional accuracy or even build failures [179, 180]. These simulations allow designers to test different scan strategies, adjust support structure placement, and anticipate the need for geometric adjustments before the first part is printed [181, 182]. Advanced process simulation approaches employ multiscale models that link microstructure evolution at the melt pool level to component-scale mechanical properties [183] or employ digital twins that fuse simulation with real-time sensor data to monitor and correct any deviations during production [184].

Within mechanical systems, one prominent SDD approach includes FEA and has been widely adopted due to their ability to describe the physical state of an object and also simulate its behaviour in a design environment [162]. As a numerical method that discretises continuous structures into smaller elements, FEA solves governing equations for stress, strain, temperature, and displacement across the entire geometry, making it particularly valuable for evaluating the intricate features and complex geometries, such as lattice structures, that AM enables.

2.5.3 SDD of lattice structures

For lattice structures, FE-based numerical modelling has been predominantly used in their design and prediction of mechanical properties [66, 74, 185], enabling faster prediction by reducing the efforts that would have otherwise required conducting experimental investigations. However, the accuracy of FE-modelling results is often limited by the material model, mesh representation, and geometrical model [132]. FE-based numerical modelling also makes it easier to understand the behaviour of lattice structures, for instance, through simulations of stress-strain distributions and failure modes, as reviewed in Obadimu and Kourousis [64]. Some of the most commonly used commercial software include ANSYS [38] and ABAQUS [74]. Together with emerging tools for lattice structures design, SDD provides a cohesive approach that exploits the geometric freedom offered by these structures while systematically addressing the unique process-specific challenges.

When lattice structures are additively manufactured, their as-printed mechanical characteristics often significantly vary [186], requiring complete characterisation. Employing FE-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 [74, 187, 188], the main is typically for validating the numerical model. Given that extensive experimentation for complete characterisation is expensive and time consuming, researchers have been increasingly turning to integrated simulation-driven design approaches. These approaches combine numerical modelling with data from experimental characterisation of as-printed structures, such as, lattice structures, to refine the numerical model, gain a deeper understanding of mechanical behaviour, and guide the optimisation of structures for target performance under real as-printed conditions [186, 189, 190].

3 Research Methodology

This chapter outlines the research methodology adopted in this thesis. An overview of the research[5] design, followed by the research process and research methods concerning the data collection and analysis techniques is presented. The chapter also reflects on the quality of the research, addressing aspects of validity and reliability, and highlights any limitations.

3.1 Research design

The presented thesis includes five studies, employing a mixed-methods approach combining qualitative literature analysis and quantitative experimental investigations, using diverse data collection and analysis techniques. The research follows an adapted version of the Design Research Methodology (DRM) proposed by Blessing and Chakrabarti [191], which is often used in engineering design research to provide scientific structure and guidance. Although alternative approaches, such as spiral models [192] or journey-to-validation frameworks [193] place greater emphasis on continuous iteration, DRM is particularly appreciated for providing clear structure, traceable connections between studies, and is generally suited to prescriptive design research. Hence, it has been chosen as an appropriate methodological foundation for this thesis.

In this thesis, DRM is not treated as a fixed structure but interpreted in a flexible manner, with individual stages emphasised or adapted according to the nature and objectives of each study involved. In this way, this thesis attempts to preserve the methodological rigour and structure of DRM while allowing flexibility to address the unique aspects of the problems investigated. DRM as a generic research methodology supports in linking research questions and supports in addressing them systematically through four iterative stages, i.e., research clarification, descriptive study I, prescriptive study, and descriptive study II, as further detailed in Section 3.2.2. Together, these stages provide a clear and transparent connection between the

[5] Partly based on Dash (2023) *Design of flexible lattice structures. A design for additive manufacturing perspective* (Licentiate Thesis), Lund University, Lund, Sweden

research questions, empirical observations, and the development and evaluation of research outcomes of this thesis.

The first stage, i.e., research clarification involves identifying the research problem and establishing the need for a particular study through literature and problem analysis. The second stage, i.e., descriptive study I, focuses on exploring the current state of practice and influencing factors through observations, analysis, or empirical studies. This stage is followed by the third stage, i.e., prescriptive study that involves developing and proposing design support, such as methods, models, or solutions based on the insights from the previous stage. The final stage, i.e., descriptive study II involves evaluating the proposed support in practice to validate its impact and refine the research outcomes. Each stage of DRM can loop back to earlier ones, enabling continuous improvement and validation.

3.2 Research process

3.2.1 Research timeline

The research process in accordance with the timeline of the doctoral studies have been presented in Figure 10.

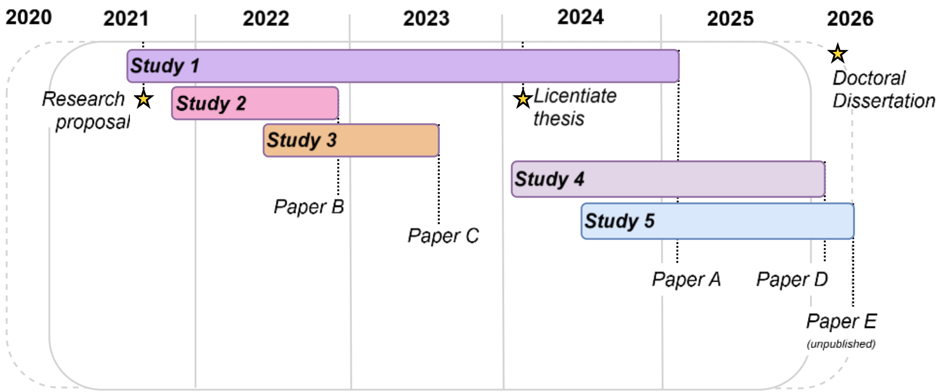


Figure 10: Research process – Timeline

During the course of the doctoral studies, five studies were carried out (Studies 1 to 5), resulting in five papers (Papers A to E) which formed the basis of this thesis. Although the presented timeline appears linear, the actual research process was iterative and evolved throughout the timeline. The work involved several rounds of exploration, experimentation, and reflections. Even attempts that did not produce the expected results were valuable, as they helped refine each study and steer the research in the right direction. Moreover, the process did not always follow the planned schedule, reflecting the unpredictable nature of research and academic publishing. For instance, Study 1 was conducted early in the doctoral research, resulting in Paper A, which, although initiated early, was published later than some of the subsequent studies.

Throughout this evolving and iterative process, each step in the research process was guided by the RQs, which helped decide what to do next, what delimitations to set, and which methods were most suitable for moving closer to the answers. Hence the order of the RQs played an important role in shaping how the work progressed. While Figure 11 maps the studies onto different stages of the adapted DRM, these stages were not explicitly defined at the start of the research. As the research developed, the boundaries between the stages became clearer, allowing the studies to be placed in their respective DRM stages.

The research was initially inspired by the STEPS project, which focused on exploring bio-based alternatives to PUR foams and considered the potential of 3D-printed foam structures. This motivated an early exploration of structural concepts capable of achieving foam-like functionality. Through this investigation, strut-based lattice structures emerged as a promising solution. Building on this, the thesis focused on designing AM-based lattice structures. Over time, this developed further into the idea of considering the dual perspective in DfAM, which has been referred to as DDfAM throughout the thesis. This was done in order to account for both the design opportunities offered by lattice geometries and the manufacturing constraints specific to the AM process. This perspective also aligned well with the ongoing research on DfAM within the Division of Innovation, allowing the research to build on and extend existing expertise.

The research process also included key milestones beyond the studies themselves, as illustrated in Figure 10. The first step of the doctoral studies resulted in a formal research proposal, which defined the scope, objectives, and preliminary methods. As the work progressed, the licentiate thesis provided an intermediate milestone, consolidating early findings and preparing the foundation for future work, ultimately leading the final milestone of doctoral dissertation.

Overall, the research journey evolved from a broad exploration of DDfAM research landscape to the development and validation of a design approach for generating flexible lattice structures aligned with DDfAM. Each step in the research process was built upon the previous one, forming a logical and iterative process, gradually addressing the overall research objective, presented previously in Section 1.3.

3.2.2 Mapping the studies to DRM Stages

The adapted DRM used in this thesis is illustrated in Figure 11, which shows how each study maps to specific DRM stages, combining the RQs, the resulting papers, and the research methods adopted in each study.

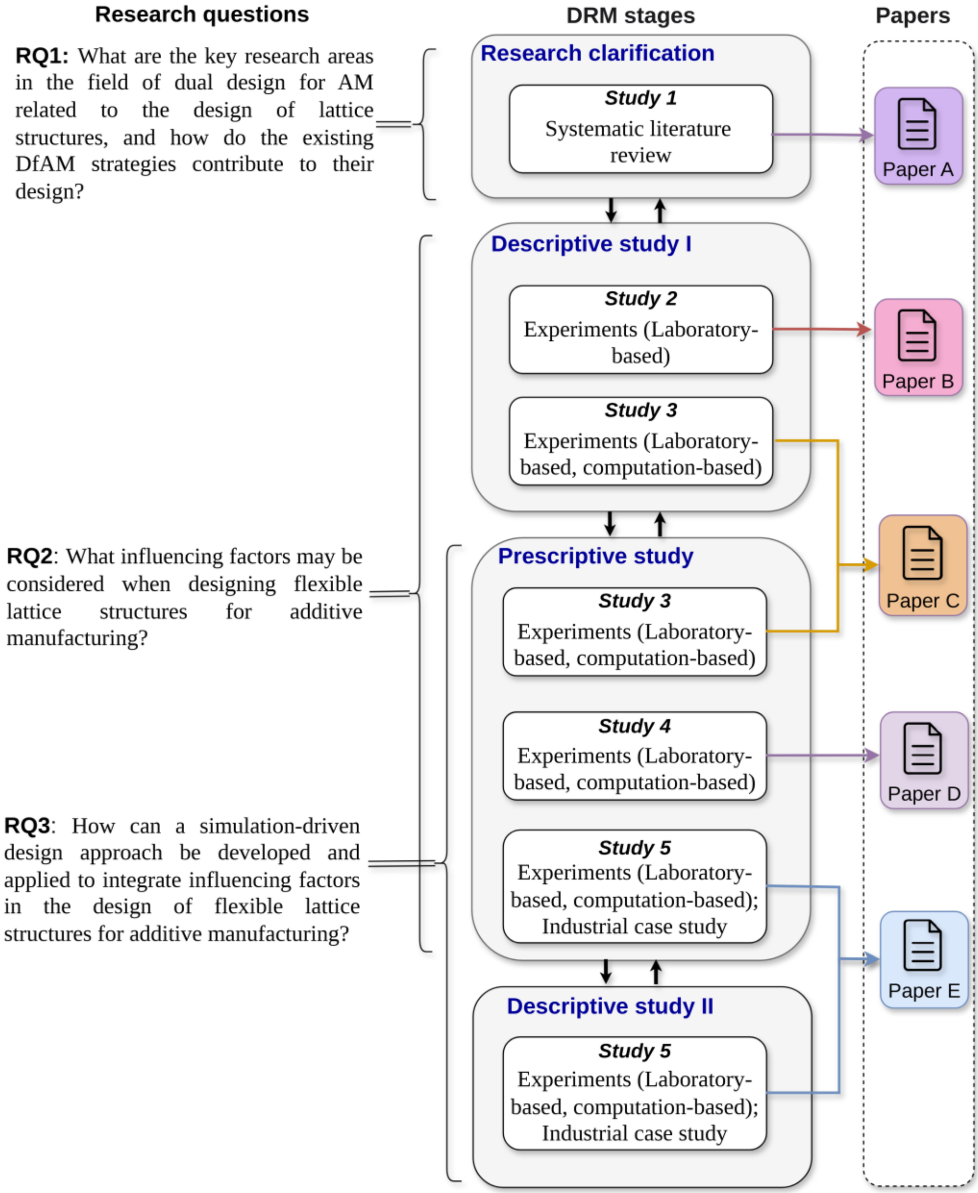


Figure 11: Research process – DRM stages, showing correlation between conducted studies, RQs, resulting papers, and research methods corresponding to each studies.

Each DRM stage is linked to specific studies that collectively build upon one another, reflecting the iterative and cumulative nature of the research. All three research questions address different aspects of the overall research objective. RQ1 focuses on exploring the state of the art in DDfAM, while RQ2 and RQ3 examine other complementary aspects of the objective. Although RQ1 is relatively standalone, RQ2 and RQ3 are more sequential in nature, building on insights from previous stages.

Building on the overview presented in Figure 11, the following sections elaborate the research process by explaining how each DRM stage aligns with conducted studies and the concerned RQs.

- *Research Clarification (Stage 1):*

In the first stage of the DRM, the focus was on clarifying the research direction and defining the scope of the first RQ. At this early stage, the research did not yet focus specifically on structural flexibility, rather, the objective was to understand how DDfAM is implemented within an engineering design process, as outlined by Pahl, et al. [79].

To achieve this, a systematic literature review (SLR) was conducted in Study 1 to map the state of the art in DDfAM, highlighting key research areas and how they relate to each other, including both established practices and emerging trends. Although the review was not specifically focused on lattice structures, the insights helped inform the design strategies commonly used for these structures and provided a foundation for adopting DDfAM for their design.

Based on the review, RQ1 was refined to investigate how DDfAM has been applied to lattice structure design and to identify which areas have been well studied and which are still under-explored. Particular attention was given to design strategies commonly reported in the literature that support DDfAM. While a standalone focus on these design strategies can provide useful insights, it can miss the interdisciplinary aspect typical to the field of DDfAM. Therefore, uncovering their inter-relationships was essential for a complete picture, hence was also emphasised in Study 1. A detailed account of the literature review and its findings is presented in Paper A.

In the original DRM, SLRs are typically performed in Stage 2, but in the adapted version of DRM, the review was conducted at Stage 1 to establish the groundwork for the later stages of the research.

- *Descriptive Study I (Stage 2):*

Narrowing the broader focus of Stage 1, this stage focused on designing lattice structures, specifically with structural flexibility as the main objective. Guided by DDfAM, the goal was to identify factors, including geometry-specific parameters and manufacturing constraints, that directly influence the design of these lattice structures. This was necessary in order to answer RQ2. Some of the influencing factors, identified in Study 1 for generic lattice structures, rather than specifically for flexible lattice structures, were used to provide insights during this DRM stage.

To address RQ2, empirical studies were conducted in Studies 2 and 3, (resulting in Papers B, and C respectively) to identify factors that affect part design during the design process, excluding those that can only be adjusted at the printing stage, such as scanning speed and strategy, among others. SLS printing with a bio-based material, PA 1101, was selected for these studies. In Paper B, two such factors were investigated to see how they affect structural flexibility. Furthermore, an additional factor was investigated in Paper C. With the information gathered from these studies, the next challenge was how to incorporate these factors into the design process.

As the overall research objective is to incorporate a SDD approach, the next step involved using FE-based numerical modelling; accordingly, FE simulations were employed. These simulations are widely employed in SDD within engineering design processes because they allow for systematic evaluation of multiple factors, enable rapid testing of different design scenarios, and provide quantitative data through virtual analysis. Therefore, such simulations were used for incorporating the factors identified in this stage to better examine their influence on the behaviour of flexible lattice structures. The first step towards this was taken in Study 3.

The main challenge, however, addressed as part of RQ3, was to develop an SDD approach that incorporated the identified factors to support DDfAM of flexible lattice structures.

- *Prescriptive Study (Stage 3):*

In Stage 3, the focus was on developing and applying an SDD approach to support the design of flexible lattice structures for AM. This directly addresses RQ3, which concerns how such an approach can be developed and applied to integrate the influencing factors identified in earlier DRM stages, into the design process.

To achieve this, FE-based numerical modelling was employed and calibrated using mechanical and experimental data to account for the relevant influencing factors. The input for calibration was obtained from the design and testing of representative test artefacts in Study 3, resulting in Paper C. In this paper, the first strut-based test artefact was introduced that served as a medium for integrating FE simulations into the design process, enabling the inclusion of as-printed geometry and material characteristics derived from the physical experiments.

Building on this, Paper D, resulting from Study 4, presented a more adaptable strut-based test artefact, designed for bending-dominated deformation which allowed for incorporation and variation of multiple influencing factors simultaneously. This type of deformation typically involves a compliant force-displacement response, making it suitable for flexible lattice structures. In both Papers C and D, experimental measurements, such as force responses, were used to calibrate material parameters for the numerical model and validate the simulation outcomes, maintaining accuracy between the printed and the numerically calibrated structures. Moreover, the CAD models used in these simulations were updated to reflect as-printed geometrical properties to ensure close alignment between experimental and numerical results.

Extending these strut-level investigations, the final study (Study 5, resulting in Paper E) developed an SDD approach at the full lattice scale. This approach advanced the numerical modelling presented in Paper D, allowing the investigation of how strut-level factors influence overall structural flexibility of lattice structures, while also incorporating their as-printed geometric and material characteristics. Through this iterative experimental-numerical process, the approach integrated key factors influencing structural flexibility into the design of lattice structures. In this way, it provided a structured way to connect experimental observations with numerical modelling, forming the core design support developed in this Stage 3.

While Studies 4 and 5 are formally mapped to this stage (Stage 3) in Figure 11, they also contributed to RQ2 by identifying additional influencing factors, also refining and validating them through experimental-numerical integration. This overlap illustrates the iterative nature of the PhD process, in which later studies not only addressed new questions but also strengthened and refined earlier findings.

- *Descriptive Study II (Stage 4):*

This stage focused on validating and refining the design support developed in Stage 3. It addressed the application part of RQ3, which concerns how the SDD approach can be applied in practice. Thus, the main focus was on testing and validating the numerical model that the SDD approach is built upon.

Guided by the broader aims of the STEPS project, the upholstery application within the furniture industry served as a motivating case for Study 5, where 3D-printed flexible lattice structures could be used as alternatives to conventional furniture upholstery foams. To this end, Paper 5 applied the SDD approach at both lattice-level and product-levels. At the lattice level, five different lattice variants were designed to replicate the mechanical responses of reference PUR foams with varying stiffness grades. One of these lattice variants was subsequently implemented at the product level to demonstrate scalability under practical design constraints. Product-level validation was illustrated through a real-world case exemplification involving cushioned headrests for office chairs; however, no additional experimental testing was conducted on the final product. Overall, Study 5 combined virtual design and physical testing of strut-based lattice structures to support validation of the developed SDD approach.

3.3 Research methods

Across the five papers (Papers A to E), the presented thesis uses both qualitative and quantitative methods. An overview of these methods is presented in Figure 11, with additional details provided in the following sections.

3.3.1 Literature reviews

An SLR was conducted in Study 1 (Paper A) following the procedure proposed by Snyder [194]. The review focused on peer-reviewed journal articles and review papers published in English between January 2000 and February 2024, sourced from Scopus and Web of Science databases. The search string incorporated both the phrase "Design for add* manu*" and its commonly used abbreviation "DfAM." A three-stage screening process adapted based on the PRISMA reporting guideline [195] was used for screening the literature. At each screening stage, each author independently reviewed and categorised the articles as *'yes', no',* or *'maybe'*. Content analysis [196] was employed to identify key research areas, providing an explorative overview of the research landscape in DDfAM. Quantitative methods, including frequency of occurance analysis together with chord diagrams were used to visualise the inter-relationships between these key areas.

3.3.2 Laboratory-based experiments

Laboratory-based experimental investigations were central to Studies 2,3, 4, and 5, corresponding to Papers B, C, D, and E, respectively. In Paper B, mechanical testing using uniaxial compression was performed on 3D-printed strut-based lattice structures. Experimented samples were visually examined (no formal inspection) to note any material failures like broken struts. Further, a quantitative measure was used to calculate the plastic deformation in these samples. In Study 3 (Paper C), two sets of experiments were conducted on samples of a 3D-printed test artefact designed for the study: one involving geometrical measurements and the other involving uniaxial compression testing. The mechanical response was analysed using radar charts and force-displacement curves plotted in MATLAB, a numeric computing software platform. The 3D modelling of the test artefact in this study was carried out using Rhinoceros 3D, together with Grasshopper, a visual programming tool that operates within Rhinoceros 3D. Paper D extended this work by introducing a customisable test artefact that allowed variation in different geometric parameters at the same time, modelled using CREO. Compression testing was performed to record force-displacement responses, while geometrical measurements were taken to capture manufacturing deviations. The experimental recordings were visualised and analysed in MATLAB, as presented in Paper D. Building on these insights, Paper E conducted quasi-static uniaxial compression tests on three reference PUR foams of varying stiffnesses, typically used in furniture upholsteries. Similar experiments were also performed on 3D-printed lattice structures that were designed to replicate these reference foam behaviours. All compression tests were video recorded, and the resulting data were compiled and processed using Excel© and MATLAB.

3.3.3 Computer-based experiments

Finite element simulations were used to develop predictive models for evaluating the compressive performance of 3D-printed thin strut-based structures. These simulations were conducted in ANSYS, a commercial computation platform, and applied across Studies 3 (Papers C), and 4 (Paper D), and using Karamba3D, a parametric engineering tool embedded in Rhinoceros-Grasshopper environment for Study 5 (Paper E).

In Study 3, an initial numerical model was calibrated against experimental results to account for observed manufacturing deviations in 3D-printed test artefacts. Both the data from experiments and computations were compared using graphical analysis in MATLAB.

Building on the modelling principles established in Paper C, Study 4 (Paper D) developed a numerical model at the strut level, specifically targeting bending-dominated structures. The model replicated the experimental compression test setup. Parametric optimisation was conducted in ANSYS using an adaptive single-objective algorithm, while Curve Fitting Toolbox in MATLAB was employed for parametric fitting and response surface analysis to establish a predictive model relating material properties with geometry.

Study 5 (Paper E) subsequently built on this predictive model by incorporating calibrated strut-level material properties into a beam-element FE model and extending its application to lattice level using nonlinear structural analyses in Karamba3D. Furthermore, this model enabled a real-world case exemplification, expanding the focus from lattice level to product level.

3.3.4 Industrial case studies

Study 5 (Paper E) represents the final stage of the research, focusing on case exemplification within an industrial context. A portion of the study investigated the development of bio-based 3D-printed flexible lattice structures intended to replace conventional PUR foam-based cushioned headrests in office chairs. This exemplification served as product-level validation of both the numerical model and the SDD approach developed in this thesis. Although not a full-scale industrial study, it demonstrates the real-world applicability of the proposed SDD approach.

A demonstrator of the headrest was also manufactured as part of this validation, as presented in Paper E.

3.4 Reflections on research quality and limitations

Validity and reliability are the two determinants essential for meaningful interpretation of data [197] and have been used to assess research quality in this thesis. Validity refers to the extent to which research accurately measures what it is intended to measure [196]. In the context of this thesis, it involves ensuring that the studies truly investigate what they are meant to study.

Reliability concerns the ability to repeat the study and get the same results, given the same conditions [198]. In this thesis, it relates to ensuring that the research process and results are consistent and could be reproduced under similar circumstances.

The mixed-method approach involved different data collection and analysis techniques to strengthen the credibility of the results [197]. The presented thesis includes five studies wherein research quality has been ensured in different ways. The first study (Study 1) was carried out using a rigorous and systematic approach [194], following established guidelines for systematic literature reviews. A three-stage screening process adapted based on the PRISMA reporting guideline [195] was used to enhance research validity and reliability of the review process. At each stage, each author independently reviewed the articles, which minimised subjective bias and improved consistency in selection. All stages of the SLR and their corresponding results were carefully documented, and electronic sources were handled consistently enabling transparency and traceability [199]. To further strengthen reliability, researcher triangulation was ensured by actively involving multiple researchers throughout the data collection and analysis process, increasing confidence in the results.

In the experimental studies (Studies 2, 3, 4, and 5), reliability was built through careful experimental planning, detailed documentation, and transparent reporting of any deviations during testing. Visual representations of the methodology, as well as the experimental setups and equipment, were included in respective papers to support readers in reproducing these studies, if needed. The experimental setup gradually improved from Studies 2 to 3 to build a foundation for the subsequent studies. Preliminary experiments were conducted to validate the planned setups before the main studies commenced, ensuring that the equipment, material, and AM process were appropriately selected and consistently applied, thus facilitating repeatability. During the early studies, several considerations were addressed, such as evaluating bio-based materials aligning with the objectives of STEPS project [57] and selecting AM processes that are compatible with these materials while also ensuring scalability for 3D printing. The same SLS machine, materials, and process parameters were maintained across most studies, including centered build plate positioning of test samples and appropriate print orientation selection, to reduce variability. Complete transparency was maintained in reporting these details to support replicability, supported by Supplementary materials wherever necessary. Such consistent approach and detailed methodological descriptions improve reliability through reproducibility [191], allowing other researchers to verify the consistency of the results [199].

Some steps were also taken to capture data more accurately, for instance, video recording compression tests for precise readings, performing quasi-static loading, and correcting for test equipment stiffnesses, wherever necessary. In addition, steps were taken to minimise measurement errors. Samples were allowed to stabilise before deformation measurements in Study 2 to reduce stress relaxation effects, and repeated measurements across multiple samples in Studies 3, 4, and 5 were performed to reduce the influence of random errors relative to the observed effects. Faulty samples were excluded where necessary, as in Study 4. Statistical treatment of data also played an important role in ensuring the research quality. Average values were used to represent stable and representative estimates, while in some cases, such as Study 3, extreme cases were examined separately to consider the worst-case scenarios.

As the research advanced into simulation-based investigations (Studies 3 to 5), the focus broadened to the development of numerical models, ranging from strut-level (Studies 3 and 4) to lattice-level (Study 5) investigations, with verification and validation (V&V) performed throughout [200, 201]. Following the simplified modelling process proposed by Sargent [200], verification assesses whether we build the model correctly, i.e., whether the computer code and calculations are implemented properly and work as intended, without mistakes. On the other hand, validation evaluates whether the correct model is built, i.e., whether the model is accurate enough to represent the real system for the purpose it is being used for [200]. In these studies, mathematical models (referred as conceptual models in [200]), representing the real system in simplified form were defined through clearly stated assumptions and idealisations regarding deformation mechanisms, supported by compression testing of representative 3D-printed test artefacts and/or full-scale lattice structures (e.g., bending-dominated structures with thin, uniformly cross-sectioned struts in Study 4 & 5).

Preliminary simulation tests were performed to validate these models, to define operational ranges, and to avoid any unwanted effects such as buckling. These models were then translated into simulation models (referred as computerised models in [200]) implemented as FE simulations with consistent geometry transfer, solver settings including time step sizes and convergence criteria, and boundary conditions (e.g., 3D mesh elements in Study 3 and 4; beam-element based representations using non-linear large deflection analyses settings in Study 5). These simulation models were validated by comparing simulated responses with experimental responses (e.g., through compression tests) and sensitivity analyses were performed to evaluate the influence of input/internal parameters of the model to determine its effect on the model's behaviour or output as done in Study 4 and 5. Such techniques thus helped confirm that the studies measured what they intended to [196].

Statistical measures such as root mean square error (RMSE) and goodness-of-fit tests were used, particularly in Study 4, to quantify the agreement between simulated and experimental results. These analyses demonstrated both validity and reliability, while empirical relationships established within a 95% confidence interval indicated the practical significance of the findings [197]. Clear criteria were applied to identify and remove outliers or erroneous data, with additional checks performed to assess the sensitivity of results to their exclusion. Moreover, the fidelity of the models increased progressively from Study 3 to Study 5 as the simulation process became more refined and representative. Together, these steps strengthened the validity of the models and improved the reliability of the numerical results across studies within the intended operational domain. More than one researcher was involved in analysing the same data to triangulate the observations during these preliminary simulations, ensuring inter-rater reliability [196].

Overall, throughout the research, data compatibility and smooth data transfer was ensured between CAD, simulation, and printing software to minimise any loss of information. Within the appended papers in this thesis, results were visualised using different formats, relevant for correct interpretation of results. These formats range from chord diagram (Study 1), radar chart (Study 3), bar chart (Study 4), line plots (Study 3, 4, and 5) to response surface plot (Study 4), supporting clear interpretation and traceability.

Finally, prior to submission to publication outlets, senior researchers peer reviewed the research outcomes for each study, aligning with the recommendations made by Yin [199], thereby enhancing the validity of the conducted studies. Throughout the research process, extensive documentation was maintained, including empirical data, video recordings of experiments, meeting minutes, coded and analysed data, as well as a comprehensive record of data collection methods. This ensured that there is a clear and traceable account of the research trajectory, from initial research questions to final conclusions [196].

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. For instance, in Study 1, considering the breadth and depth of the DfAM field, the selection criteria and the subsequent classification of findings involved a subjective analysis, thus limiting reproducibility to certain extent. 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. In terms of validity, Study 2 involved experimentation on nine test samples to investigate deformation behaviour. While the study provided valuable initial insights, a larger sample size would be necessary in future investigations to strengthen the validity of the conclusions drawn in Paper B. Similarly, while Study 3 utilised 3D mesh elements, a finer mesh and an enhanced finite element model would more accurately capture localised mechanical effects and improve prediction accuracy.

Additionally, in Study 4, one experimental trial failed and was excluded from the analysis. Although this was transparently reported in Paper D, the inclusion of an additional, successful trial might have increased the robustness and accuracy of the findings. Outliers were identified and excluded; while justifiable, this approach could introduce bias or overfitting and may not account for the full range of variability in key influencing factors under study. Moreover, the underlying causes for these deviations remain uncertain, which might introduce some ambiguity regarding the validity of the dataset.

Although two samples per case sufficed to establish the empirical relationship in Study 4, additional samples would have strengthened the evaluation of statistical significance. This consideration was addressed in Study 5, which was conducted with three samples per case. In Studies 4 and 5, geometrical deviations were considered specifically in terms of average variations in strut diameter values without accommodating form deviations, causing the numerical models to assume geometric uniformity along the struts. In practice, local variations such as ovality or tapering (as observed in findings from Study 3), may not be adequately captured by this averaging approach. This simplification may reduce the reliability of the results, particularly given that geometric deviations can vary significantly across different print batches due to inherent process fluctuations.

An elastic-perfectly plastic material model was used to avoid stress singularities in simulations as part of Studies 4 and 5. This simplification may oversimplify the actual material response in thin struts when complex loading scenarios get involved, potentially affecting the reliability of results. As such, the findings are valid only within the deformation range prior to the onset of plasticity owing to the chosen material model.

Overall, even though the outcomes of this research are adaptable, they are currently not implemented to demonstrate the generalisability for alternative materials or AM processes such as FFF or SLA which would require additional efforts in future.

4 Summaries of appended papers

This chapter presents the research[6] results by summarising the five papers appended to this thesis.

4.1 Paper A

Title: Dual design for additive manufacturing in engineering design: a systematic literature review

Introduction

The purpose of this paper was to map DfAM research within the engineering design process, focusing solely on studies adopting DDfAM. For this purpose, systematic review of 148 publications between January 2000 and February 2024 was conducted, sourced from Scopus and Web of Science databases, following the procedure proposed by Snyder [194]. The search string incorporated both the phrase "Design for add* manu*" and its commonly used abbreviation "DfAM." A three-stage screening process adapted based on the PRISMA reporting guideline [195] was used for screening the literature. Content analysis was used to group the selected publications into research clusters based on the design phases they address: *the entire design process, the early design phases and the later design phases* as shown in Figure 12. Each cluster was further analysed, and common patterns were identified according to their core focus and contributions resulting in research themes per cluster.

[6] Partly based on Dash (2023) *Design of flexible lattice structures. A design for additive manufacturing perspective* (Licentiate Thesis), Lund University, Lund, Sweden

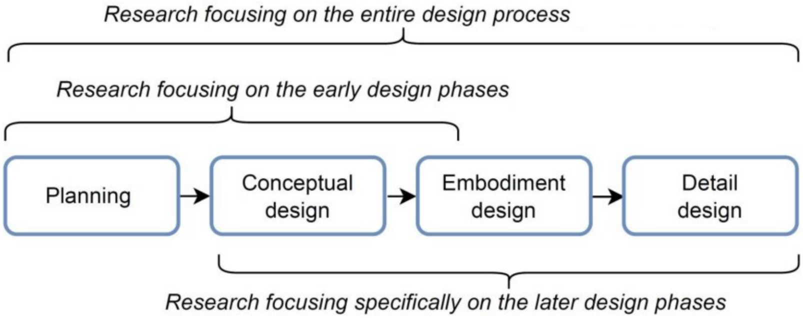


Figure 12: Research clusters relating to different phases of the engineering design process, Courtesy: Dash, et al. [202]

Based on these themes, a model presenting the landscape of dual DfAM research in relation to the engineering design process was proposed, as shown in Figure 13.

Findings

The findings in Paper A indicate that the literature focusing on DDfAM implementation primarily addresses the later design phases (65%), with comparatively little research addressing the entire design process (12%) or the early design phases (23%). Concerning the entire design process, literature mainly focuses in two themes: *component-level DfAM*, which aims to improve component capabilities, and *assembly-level DfAM*, which considers assembly-related features. In the early design phases, literature largely addresses two themes: *decision making for AM* and ways for enabling *creative or inspirational design solutions for AM*. In the later design phases, the literature was systematically reviewed and organised into eight research themes. These themes capture the main areas where design strategies relating to DDfAM implementation typically provide support: *design optimisation*, *design evaluation*, and *geometric modelling*; integrating *design parameters* and *AM-specific constraints*; addressing AM-specific *design rules and guidelines* and *design implications*; and designing *complex structures*. Because part design is largely influenced by the later design phases, Paper A further examined the relationships between these eight research themes to capture the interdisciplinary nature of the dual DfAM field. Through 36 unique pairwise theme combinations (i.e., analysing themes in pairs), the analysis revealed areas that have received substantial attention and those that remain under-explored. Figure 14 presents one such theme combination, illustrating pairs that have been extensively researched.

Although limited by certain inclusion criteria and publication types, the findings in Paper A provide a comprehensive overview of the current state of DDfAM research.

Based on the overall review results, suggestions for future research directions were proposed by discussing the characteristics and limitations of the reviewed literature.

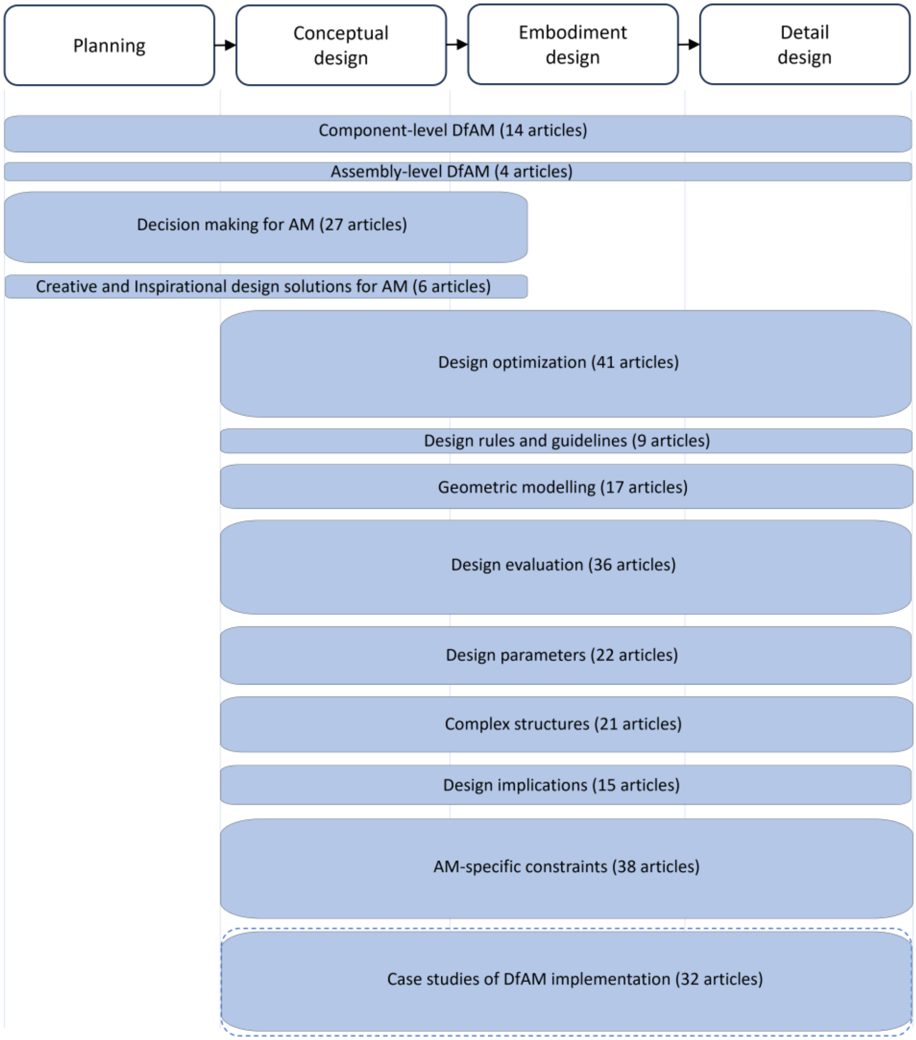


Figure 13: A model presenting the dual DfAM research landscape related to the engineering design process, Courtesy: Dash, et al. [202]

Paper A also specifically discusses the theme of complex structures. Within this theme, literature is dominated by studies on cellular structures, especially lattice structures and their variants such as functionally graded lattice structures (FGLS), conformal lattice structures (CLS), and multi-material lattices, while other forms, including auxetic, gyroid, and voronoi structures, remain less explored. Pairwise theme combinations involving complex structures show how different design strategies have been applied to lattice structures, highlighting well-researched directions as well as clear gaps.

Figure 14: Pairwise theme combination results, only shown for highest number of combinations (extensive research), Courtesy: Dash, et al. [202]

The findings highlight that current design strategies for lattice structures are well developed for FEA, primarily supporting material and structural performance evaluation, but they offer limited support for integrated design and evaluation. CAD-based geometric modelling strategies mainly address single- and multi-scale modelling yet lack automation and seamless integration when used alongside design optimisation strategies. Existing optimisation strategies tend to focus on gradient-based topology and multi-scale structural optimisation, with minimal attention to size or parameter optimisation. Similarly, strategies addressing design parameters, AM-specific constraints, and design implications (e.g., cost reduction) often consider only a narrow subset of these factors.

Although manufacturability is sometimes addressed implicitly, for instance, through constraints incorporated into topology optimisation environment, strategies that explicitly ensure manufacturability throughout the design process are scarce.

No available strategies provide design rules or guidelines tailored specifically to lattice structures, and integrated strategies that combine FEA, optimisation, and CAD modelling within a single design environment also remain largely unexplored.

Contribution to the thesis

Paper A answers RQ1 by identifying the main research areas and gaps in DDfAM particularly relating to the design of lattice structures. By mapping the DDfAM landscape across the engineering design process, the paper highlights where existing design strategies are concentrated, i.e., mainly in the later design phases and where limited work exists, i.e., when addressing the entire design process or the early design phases. The detailed analysis of themes related to complex structures, especially lattice structures, provides a clear picture of which strategies are well developed, such as related to FEA-based evaluation, geometric modelling, and design optimisation; in what ways they support the design of these structures; and which ones remain underexplored. These insights helped in clarifying how existing design strategies interact and where opportunities for future work exist.

4.2 Paper B

Title: Effects of print orientation on the design of additively manufactured bio-based flexible lattice structures

Introduction

The purpose of this paper was to investigate the effect of print orientation and lattice topology on the compressive behaviour of lattice structures. Broader purpose was to provide insights for designing flexible lattice structures from bio-based materials through AM, that can replace environmentally harmful PUR foam. For this purpose, a study was conducted involving a range of strut-based lattice structures with three varying topologies, including body-centered-cubic (BCC), a BCC variant with vertical struts (BCCZ), and face-centered-cubic with vertical struts (FCCZ) and using PA 1101, a bio-based material and SLS technology. Other lattice dimensions such as unit cell size, lattice size, and strut diameter were kept constant. These lattice structures were printed in three different orientations each, i.e., XY, XZ, and YZ, as shown in Figure 15, resulting in 9 printed samples. Their compression behaviour, used as an indicator of flexibility, was investigated using uniaxial compression tests for each test sample, i.e., corresponding to each lattice topology and printing orientation combination.

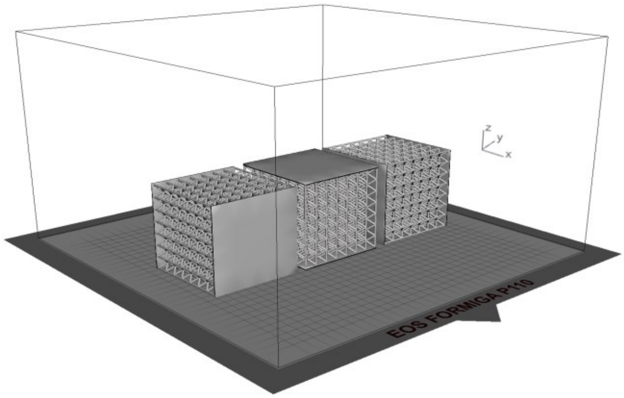


Figure 15: Printing of lattices in three different orientations (left to right): YZ, XY, and XZ, Courtesy: Dash and Nordin [203]

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 on the deformed samples to assess their deformation pattern and material failures, plastic deformation was assessed by calculating deformation percentages i.e., percentage change in height, post compression. The slightly varying initial heights of the printed structures (i.e., prior to compression) were compensated within these calculated percentages. To exclude any effects of stress relaxation, the printed structures were left to rest for 24 hours before measuring their deformed height.

Findings

The findings indicate 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. The best performing structure with least plastic deformation and material failure was BCC. The print orientation with least material failure was found to be XZ orientation. Moreover, for structures with vertical struts, it was found that XY orientation was not suitable due to visible broken struts. Although a larger sample size would be required to fully explore compression behaviour, the findings clearly demonstrate that these two parameters are crucial when aiming to achieve flexible lattice structures. Additional research is needed to evaluate these effects across other material-process combinations.

Contribution to the thesis

Paper B answers RQ2 by identifying influencing factors that may be considered when designing lattice structures for AM, particularly in applications where flexibility is essential. It demonstrates how geometry- specific parameters (specifically lattice topology) and process-specific parameters (specifically printing orientation) affect their mechanical behaviour. The findings demonstrate that print orientation strongly affects how a lattice deforms and whether it fails, while the topology mainly governs the amount of permanent deformation. By revealing how these factors shape the mechanical performance, the paper clarifies how they should guide design choices in AM, for instance, selecting a topology to achieve a desired level of flexibility or choosing an orientation that minimises failure risks. These insights therefore help inform more deliberate design decisions concerning flexible lattice structures.

4.3 Paper C

Title: Towards realistic numerical modelling of thin strut-based 3D-printed structures

Introduction

The purpose of this paper was to develop a numerical model for predicting the compressive strength of a thin strut-based 3D-printed test artefact. Thin strut-like features are common in lattice structures used for lightweight applications, and their geometry makes them particularly sensitive to manufacturing-induced deviations [204]. Owing to the layer-by-layer technique, as-printed structures often exhibit mechanical characteristics that differ from their idealised, as-designed counterparts with such deviations being even more pronounced for thin struts [186]. Therefore, capturing these deviations is essential to accurately predict their structural behaviour. To address this issue, Paper C presents a numerical model that explicitly incorporates manufacturing-induced deviations to evaluate their influence on compressive strength.

In this study, an FE-based numerical model was developed by incorporating both geometric and material deviations observed in as-printed structures. The deviations were captured from a test artefact (see Figure 16), designed to represent thin strut-like features with strut diameter of 0.8 mm. Test samples were 3D printed using PA 1101 and SLS technology with all samples printed in a fixed orientation and positioned at the centre of the build plate, equidistant from each other, eliminating any effects of print orientation or build plate positioning.

Findings

The findings of this study revealed geometric deviations in printed samples in the form of tapered strut geometry with an elliptical cross-section, as shown in Figure 16. These geometrical deviations were measured and incorporated to modify the as-designed CAD geometry. The updated geometry was used in the numerical model to predict the compressive strength for the test samples.

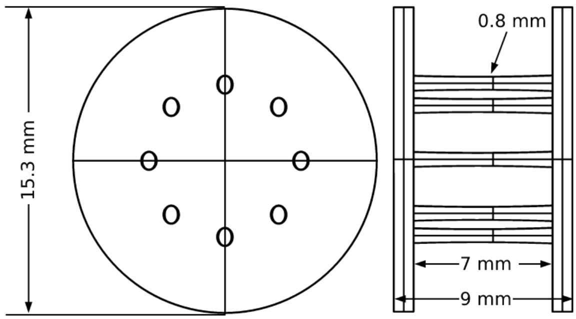


Figure 16: CAD model showing the elliptical cross-section and tapered strut geometry, Courtesy: Dash and Nordin [205]

The compression strength of printed samples was evaluated using uniaxial compression tests by measuring the force-displacement response and peak load. Material deviations were identified from the experimental results, for instance, Young's modulus of the as-printed material was found to be 950 MPa, compared to the base material value of 1650 MPa. This reduction is likely due to moisture absorption by samples at room temperature due to their high surface-to-volume ratio [206] or the printing process influencing Young's modulus in thin struts [207]. Subsequently, experimental results were employed to include the manufacturing deviations into a numerical model to improve its predictive capability.

As mentioned previously, while the geometric adjustments in CAD model captured the measured shape changes in the struts, they alone were insufficient to replicate realistic structural behaviour. In reality, any printed structure is not perfectly ideal, therefore, additional perturbations are necessary to better represent real conditions and trigger instabilities, if any, such as buckling. Accordingly, to further enhance the prediction accuracy of the model, FE-based perturbations were introduced by applying small nodal displacements to the ideal geometry, both with and without geometric shape adjustments. The significance of adding perturbations was seen by comparing the peak load of the as-designed CAD (i.e., ideal) geometry with and without perturbations as shown in Figure 17. Further details on the numerical modelling are presented in the full paper.

The findings also demonstrate that the force-displacement response and peak load measured from the experimental investigation are in good agreement with those predicted using the proposed numerical model up until the peak load, as presented in Figure 17 and Table 1.

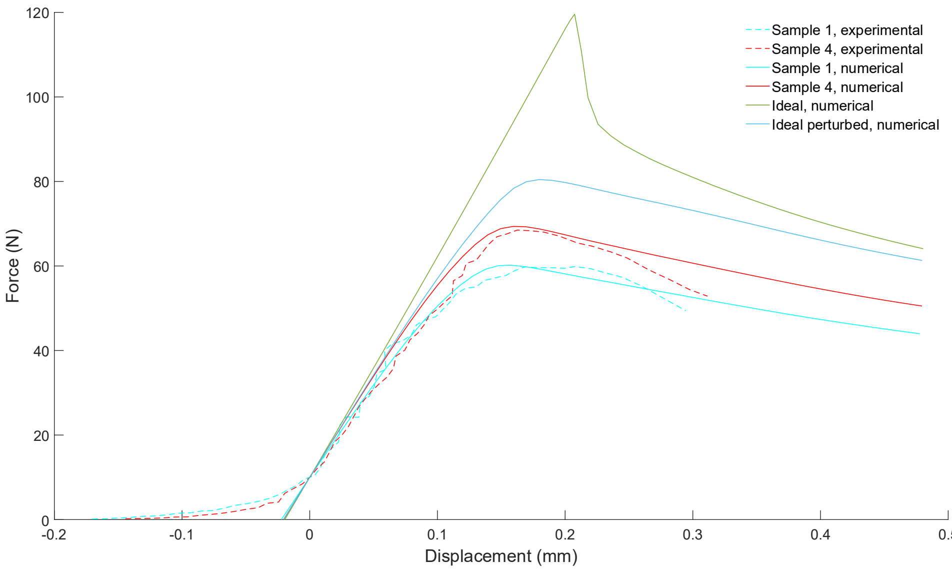


Figure 17: Force-displacement curves comparing the compressive behaviour of test samples obtained from experimentation and numerical simulations, Courtesy: Dash and Nordin [205]

Table 1: Experimental and numerical results for peak load (numerical with *), Courtesy: Dash and Nordin [205]

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

The peak load variation observed is less than 15% across the test samples which indicates the safety margin, thus reflecting the importance of taking manufacturing deviations into account. Other findings reflect that not accommodating geometrical deviations into the numerical model overestimates the peak load, for instance, peak load of sample 4 is overestimated by 17.4% when geometrical deviation was not accommodated (see Table 1). The average measured deviation of the strut diameters between the as-designed CAD model and as-printed test samples was found to be 0.075 mm (around 9% of the as-designed strut diameter), indicating the importance of design tolerances to be considered when SLS-printed thin parts are involved. Although the proposed numerical model was simplified and limited to predicting samples' behaviour until the onset of plasticity, the outcomes of this study nevertheless highlighted the importance of accounting for manufacturing deviations when designing parts for AM.

Contribution to the thesis

Paper C contributes to answering RQ2 and RQ3 by demonstrating that manufacturing-induced deviations, specifically geometric and material deviations, are key factors influencing structural performance and can be incorporated into an FE-based SDD approach for AM parts with thin strut-like features.

Although the study focuses on a generic strut-based test artefact rather than directly on flexible lattice structures, its insights are highly relevant because lattice structures often rely on thin struts to achieve flexibility, and these features are particularly sensitive to manufacturing deviations. The numerical model developed in this work demonstrates that incorporating as-printed part characteristics significantly improves the accuracy of compressive strength predictions, highlighting the importance of considering these characteristics when designing lattice structures, including those intended to exhibit flexibility.

By showing how such deviations influence structural performance and how they can be embedded into numerical models, Paper C establishes an important first step toward an SDD approach that integrates DDfAM and supports more informed design decisions in AM.

4.4 Paper D

Title: A combined experimental – numerical approach for predicting Young's modulus in additively manufactured thin strut-based structures

Introduction

The purpose of this paper was to explicitly capture on a strut level how Young's modulus (E) of the printed material varies as a function of both strut diameter (d) and orientation (θ) while accounting for as-printed conditions, such as geometric deviations. Herein, θ indirectly accounts for printing orientation which is a factor known to influence AM part performance. This study was motivated by the fact that thin strut-based AM structures often deviate from ideal material behaviour, especially near manufacturability limits as they are more prone to process-induced variabilities [189]. In such cases, design parameters, d and θ can strongly influence mechanical properties like stiffness, but most studies focus on full lattices, making it hard to isolate these effects. This paper addresses that gap by examining these parameters at the strut level.

In this paper, a generalisable methodology alongwith a parameterised test artefact was developed, employing a combined experimental-numerical approach that isolates effects of d and θ from higher-order topology, providing clearer insights into their individual contributions. The methodology developed and demonstrated in this study using SLS-printed PA 1101 polymer structures, is presented in Figure 18.

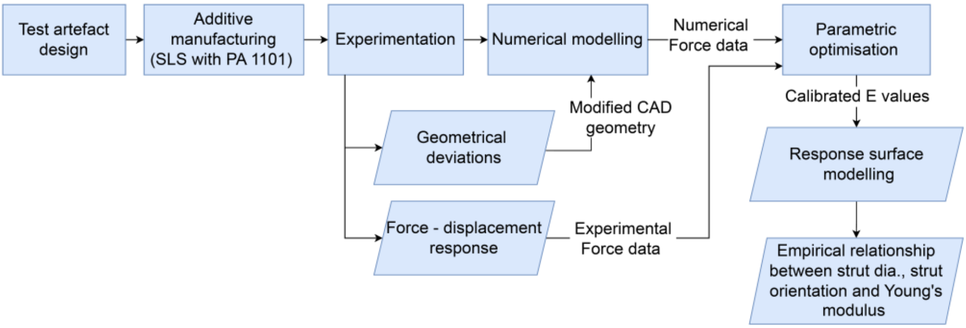
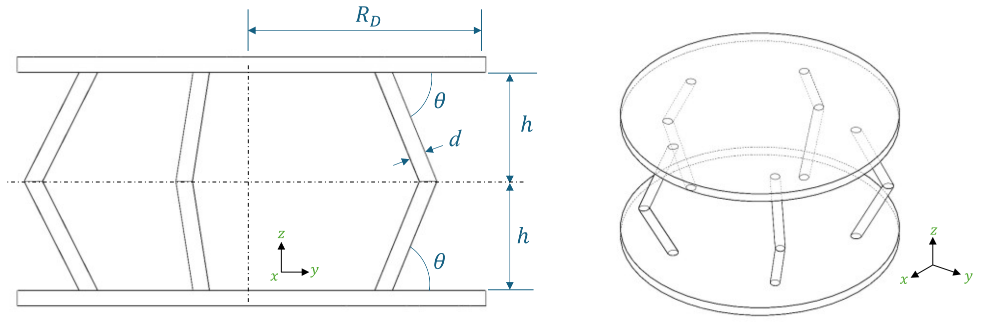


Figure 18: Developed methdology, Courtesy: Dash and Nordin [208]

Findings

This paper builds on the findings from Paper B and Paper C. From Paper B, it extends the understanding of how orientation- and topology-related effects influence the mechanical behaviour of lattice structures by investigating these factors at the strut level rather than at the level of full lattices. From Paper C, it adopts a test-artefact-based and combined experimental–numerical approach, and applies it at a finer scale (i.e., at strut-level), with a parameterised test artefact (see Figure 19), allowing independent variation of d (0.8–1.6 mm) and θ (30°–60°).

The artefact was designed to promote bending-dominated deformation under compressive loading, providing a compliant force-displacement response, while avoiding non-linear effects such as buckling or plasticity. This design ensures accurate compression testing of thin strut-based structures by avoiding non-linearities and provides reliable experimental data for subsequent calibration of a numerical model.



a) b)

Figure 19: Test artefact design a) front view and b) isometric view, Courtesy: Dash and Nordin [208]

Two test samples were printed per *d* and *θ* combination (total 24 samples) and were tested under uniaxial compression to obtain force-displacement responses. An FE-based numerical model replicating the experimental setup was developed to simulate the force reactions under nine different displacement loads used for compression testing. Given the significance of incorporating geometric deviations as was demonstrated in Paper C, the CAD models used in the FE simulations were modified to incorporate as-printed strut diameters rather than idealised dimensions. Parametric optimisation in ANSYS was used to calibrate *E* for each combination of *d* and *θ*. These results were further analysed using statistical parametric fitting techniques in MATLAB to generate a response surface based on linear 2D polynomial model, capturing the empirical relationship between *d, θ,* and *E*, as presented in Equation 1. The goodness-of-fit statistics are detailed in the full paper.

$$E = c_0 + c_1 \times d + c_2 \times \theta \quad (1)$$

where the coefficients, $c_0, c_1,$ and c_2 are 1.2648e+03 MPa, 148.3583 MPa/mm, and -8.2278 MPa/° respectively.

The findings of this study show that strut diameter and strut orientation significantly influence the Young's modulus of printed materials, with calibrated *E* values deviating up to 46% from the base material modulus. Moreover, the linear 2D polynomial model was found to effectively capture the combined influence of *d* and *θ* on *E,* in a statistically reliable manner, thereby offering a useful way to predict *E* for alternate strut configurations.

While the numerical model proposed in this study is currently limited to compressive behaviour prior to plastic deformation, it provides a foundation for future extensions to other failure modes, such as fatigue, and to other phenomena related to plastic deformation, involving crumpling, and energy absorption that will require full material characterisation.

Concerning the methodology, although demonstrated for one material and one AM technology, the methodology developed in this study could be adaptable to other AM processes, such as fused filament fabrication, by adjusting for specific geometric constraints like minimum feature size and print orientation. However, such extension would require additional studies in future.

Contribution to the thesis

Paper D answers RQ2 by showing how strut-level factors, specifically strut diameter and strut orientation, combinedly influence the Young's modulus of printed materials in thin strut-based AM structures. These insights help identify critical factors for designing struts in flexible lattice structures, as thin struts with bending-dominated behaviour provide compliant force-displacement responses suitable for achieving flexibility. Moreover, parameterised test artefact developed in Paper D allows investigation of various structural configurations and prediction of E for different strut diameters and orientations, making the applicability broader to lattice types such as auxetic, dodecahedron, kelvin, and BCC structures.

Paper D answers RQ3 by advancing towards an SDD approach. To this end, it combines FE simulations with parametric optimisation, integrating strut-level geometric and process-specific parameters to predict mechanical behaviour more accurately, which in this case is E, an indicator of flexibility. Overall, the findings build on previous numerical modelling related insights and contribute to developing an SDD approach that is centered on DDfAM, thus, supporting the design of flexible lattice structures.

4.5 Paper E

Title: Designing flexible lattice structures for additive manufacturing: A simulation-driven design approach

Introduction

This paper presents an SDD approach, centered on DDfAM, for developing flexible lattice structures with targeted stiffness characteristics. The approach integrates geometry-specific parameters, material behaviour, and manufacturing-induced deviations into a calibrated numerical model, explicitly accounting for as-printed conditions to improve predictive accuracy. This approach is illustrated in Figure 20.

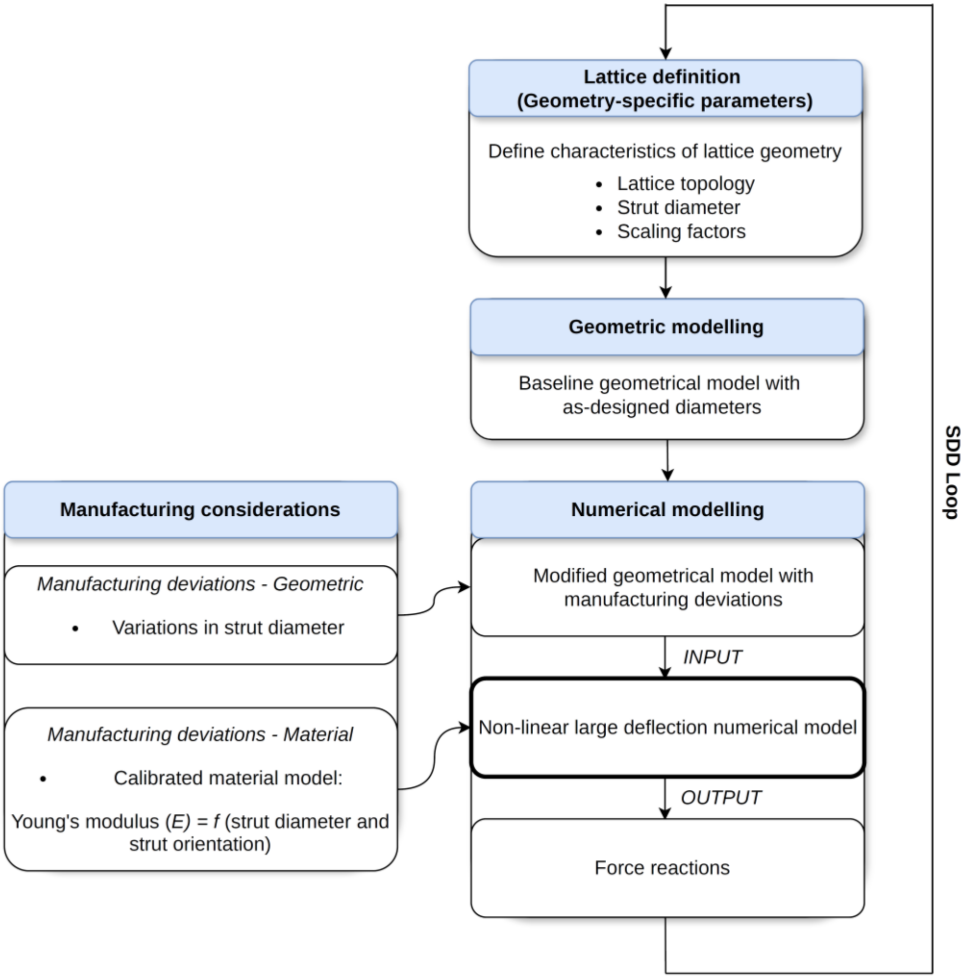


Figure 20: Proposed SDD approach for the design of flexible lattice structures, [Paper E]

Although AM enables complex lattice geometries, achieving the intended mechanical performance remains challenging since such structures require precise control over geometry-specific parameters and are sensitive to process-specific parameters, such as manufacturing-induced deviations. These challenges are particularly critical for flexible lattice structures, typically used in applications such as soft robotics, biomedical implants, vibration isolation systems, and cushioning where controlled deformation and energy absorption are essential. To address this, the proposed SDD approach systematically links geometric design with material and manufacturing considerations from a DDfAM perspective, enabling reliable design of such flexible lattice structures.

The SDD approach comprises three phases: *Lattice definition* where geometry-specific parameters for nominal lattice geometry are specified, including lattice topology, strut diameters, and scaling factors; *Geometric modelling* where baseline 3D geometrical model is generated based on the lattice parameters defined in the previous phase; and *Numerical modelling and Manufacturing considerations*, where a nonlinear beam-element FE model captures large-deflection behaviour while incorporating manufacturing-induced geometric and material deviations identified from mechanical testing of as-printed structures. Material deviations are accounted for through a calibrated material model defined in Paper D. The numerical modelling was performed in Grasshopper-Karamba3D environment.

The baseline geometrical model generated in the geometric modelling phase was modified to incorporate the identified deviations and subsequently used as input to the numerical model. The model predicts force responses under prescribed loading conditions, and these results are fed into an *iterative SDD loop*. This loop, illustrated in Figure 20, enables manual or optimisation-driven refinement of the nominal lattice geometry until the target response is achieved.

To implement the proposed approach, a nominal Kelvin-cell lattice (30 × 30 × 30 mm) with a 2 × 2 × 2 unit-cell array was defined during the lattice definition phase. Other geometric parameters included a 1 mm strut diameter and two scaling factors: uniform XYZ scaling and directional XY scaling.

The approach was validated at the lattice level by generating lattice variants to replicate conventional PUR foams with varying stiffness characteristics commonly used in furniture upholstery. The structures are fabricated using SLS with bio-based PA 1101 material.

At the product level, one of these lattice variants was subsequently implemented in the design of a cushioned headrest for office chairs.

Findings

The lattice level validation of the proposed approach generated five design variants (Variants 1 to 5) replicating the target pressure responses of reference PUR foams with three different stiffness grades (soft, moderate, and stiff foams).

Findings from compression testing indicate that the printed lattice variants closely replicate the target pressures of reference PUR foams, confirming that, through iterative adjustment of geometric parameters, specifically strut diameters and scaling factors, within the SDD loop, the approach can effectively tune lattice stiffness to achieve specific mechanical targets.

Across the five variants, average deviations ranged from -1.4% (Variant 5) to 4.3% (Variant 2), confirming that the calibrated numerical model reliably reproduces the target pressure responses across diverse geometric configurations.

Moreover, the findings, as presented in Table 2, indicate that explicitly accounting for manufacturing-induced geometric and material deviations into the design process significantly improves the prediction accuracy. The proposed approach achieved a mean error of -0.7%, compared to 21.3% between the predicted and experimental values, when deviations were not considered. These findings highlight the value of adopting a DDfAM perspective that not only exploits geometric design freedom but also systematically integrates process-induced variabilities, achieveing accurate and reliable performance predictions.

Table 2: Comparing numerical predictions with and without manufacturing deviations, [Paper E]

Design variant	***Numerical predictions***		***Experimental Pressure data [Pa]***	***Difference with deviations [%]***	***Difference without deviations [%]***
	Predicted pressure with deviations [Pa]	***Predicted pressure without deviations [Pa]***			
1	1377.0	1640.8	1339.5	2.8%	22.5%
2	3664.6	4372.7	3490.9	5.0%	25.3%
3	5344.6	6376.8	5537.9	-3.5%	15.1%
4	5209.4	6902.4	5559.8	-6.3%	24.1%
5	1372.5	1668.5	1394.0	-1.5%	19.7%
Mean				*-0.7%*	*21.3%*

Variations observed in individual samples, especially those with larger strut diameters, highlighted the effects of geometric irregularities, stress concentrations at nodes, and deviations introduced by the SLS process. These observations emphasise even more, the need to incorporate manufacturing influences into the design process.

Additionally, the findings show that the use of beam-element models with calibrated material properties substantially reduced computational time compared to solid-element models, allowing faster design iterations within the SDD loop. Each simulation required approximately 300 ms on average.

The lattice level validation of the proposed approach was demonstrated by integrating one of the designed lattice design variants into a headrest component for office chair, as shown in Figure 21. This example showed that the approach can be scaled from small lab-scale samples to a larger real-world component.

Contribution to the Thesis

Paper E answers RQ2 by showing how strut-level factors, specifically strut diameter and strut orientation (identified in previous studies) can, at lattice-level, contribute towards the mechanical performance of flexible lattice structures. It also shows how lattice size (considered through scaling factors in Paper E) serve as another geometrical parameter for adjusting the target performance.

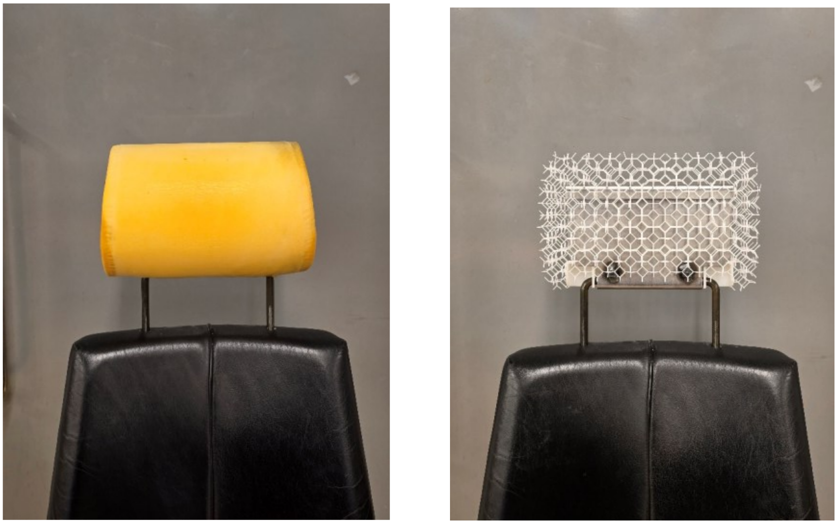


Figure 21: A case example of headrest conventional PUR foam (left) and the corresponding replacement with a 3D printed flexible lattice structure (right), [Paper E]

Building on the numerical modelling insights from Papers C and D, Paper E answers RQ3 by demonstrating how a suitable SDD approach, centered on DDfAM, can be developed specifically for designing flexible lattice structures.

It also answers RQ3 by demonstrating how the developed SDD approach can be applied at both the lattice level and the product level when aiming to design flexible lattice structures. Although, a full-scale industrial case study would be essential in future. In summary, this approach brings together geometric, manufacturing, and material considerations to predict the mechanical response of 3D-printed lattice structures and to replicate target properties comparable to polyurethane foams typically used in furniture upholstery.

5 Discussions and conclusions

This chapter discusses the findings from the studies carried out in this thesis to answer research questions and highlights the main research conclusions.

5.1 Discussions

The research objective presented in this thesis is *to advance the state of the art in dual design for additive manufacturing by enhancing knowledge on how to design flexible lattice structures that integrate both geometric and manufacturing considerations, incorporating a simulation-driven design approach*.

To fulfill the research objective, three research questions (RQs) were formulated in Section 1.3. In the current subsection, the outcomes from the five studies conducted as part of this thesis are discussed and research questions are answered, collectively addressing the research objective, as presented below:

- *RQ 1:* What are the key research areas in the field of dual design for additive manufacturing related to the design of lattice structures, and how do the existing strategies contribute to their design?

Addressing the first part of RQ1, the key DDfAM research areas that dominate current efforts in lattice structure design are identified in Paper A. It reveals a strong emphasis on *FEA-based applications* and the consideration of *manufacturing constraints*, such as size and geometric limitations. Considerable focus is placed on *geometric or CAD modelling*, alongside some research efforts to integrate *design parameters* like feature geometry and orientation, and to address *design implications* such as cost reduction. A smaller body of work addresses *manufacturability analysis* and *design optimisation*, while a clear gap remains in research efforts targeting *design rules and guidelines* specific to lattice structures.

Addressing the second part of RQ1, the following paragraphs discuss how the existing design strategies, as reported in Paper A, contribute to lattice structure design. These strategies are presented in relation to the key research areas identified above.

FEA-based strategies primarily support the analysis of mechanical performance while *CAD modelling-based strategies* facilitate the generation of lattice geometries, and *design optimisation strategies* strive for structural efficiency. Substantial research has explored FEA-based startegies which have shown to support design optimisation and consider manufacturing constraints, but to a limited extent. Moreover, integrated strategies that enable iterative feedback from simulations to inform design revisions and concurrent CAD updates, remain limited in the context of lattice structures, thereby hindering seamless integration between design and evaluation.

Similarly, although *CAD modelling-based strategies* enable both single- and multi-scale modelling, few provide enhanced modelling flexibility while simultaneously improving printability and reducing post-processing requirements. Moreover, CAD modelling for lattice structures lack automation for direct integration into optimisation environments, often requiring manual intervention and limiting modelling efficiency.

Concerning broader DDfAM considerations, existing strategies address *design implications* related to anisotropy and cost reduction in lattice structures. However, environmental concerns and key process-induced variations, such as residual stress, thermal deformation, and surface roughness, remain scarce. Concerning *design parameters*, (i.e., geometry-specific parameters including feature geometry and orientation) and certain *manufacturing constraints*, (i.e., process-specific parameters including printing orientation, support structures, and powder entrapment), have begun to receive attention, however, systematic investigation of additional influencing factors remain limited.

In terms of *design optimisation* strategies, they are predominantly centered on gradient-based topology optimisation and multi-scale structural optimisation, with comparatively less emphasis on size and parameter optimisation.

Manufacturability analysis, when considered, is typically addressed implicitly, often through constraints within TO environment, and strategies that explicitly ensure it throughout the entire design process remain scarce. Moreover, no strategies are available that address *design rules and guidelines* specific to lattice structures.

The lack of integration of FEA, CAD, and optimisation within a unified design environment represent a significant gap. This fragmentation limits the ability to develop efficient, iterative, and flexible strategies for the design of lattice structures.

Moreover, Paper A highlights that most existing studies in DDfAM for lattice structures focus on structural complexity, design freedom, and stiffness enhancement [35, 137, 209] as design goals, while structural flexibility has received limited attention. Although some work on flexible structures exists, as noted in Paper A, they are typically not based on lattices [21]. The presented thesis addresses this gap by focusing on the design of lattice structures targeted for structural flexibility, as demonstrated in the findings of Papers B, C, D, and E and further explored in subsequent RQs.

❖ *RQ 2: What influencing factors may be considered when designing flexible lattice structures for additive manufacturing?*

Addressing RQ2, this thesis identified a set of influencing factors, i.e., geometry-specific and process-specific parameters for designing flexible lattice structures specifically for AM. These factors directly influence structural flexibility, while also influencing other important considerations, such as manufacturability and material robustness.

Paper A provided an initial overview of factors commonly discussed in the broader lattice structure literature, whereas subsequent empirical investigations in Papers B to E highlighted factors specifically relevant to flexible lattice structures. Together, these studies demonstrate that achieving structural flexibility in 3D-printed lattices requires an integrated consideration of multiple parameters, as detailed below.

The first group of influencing factors relate to geometry-specific parameters, among which *lattice topology* plays a central role as it governs the deformation behaviour. This effect was clearly demonstrated in Paper B, where three strut-based lattice topologies, i.e., BCC, BCCZ, and FCCZ topologies exhibited distinct deformation behaviours despite being tested under identical conditions. In addition, lattice topology was found to primarily determine the observed plastic deformation during compression testing.

Closely related to topology are *strut diameter and strut orientation*, both of which were investigated in Paper D, which showed that these parameters directly influence the Young's modulus, E, in thin strut-based structures, with strut orientation (which indirectly accounts for printing orientation) having a stronger effect than diameter. In addition, in Paper E, *lattice size* emerges as a key geometric parameter, influencing the overall mechanical response at the lattice scale. Paper E confirmed that lattice topology, strut diameter, strut orientation, and lattice size collectively determine the mechanical behaviour of 3D-printed lattice structures.

A second group of influencing factors concerns process-specific parameters related to AM process itself. Due to the inherent anisotropy of the AM process, *printing orientation* emerged as a major factor affecting structural flexibility. Paper B demonstrated that changes in printing direction significantly influenced deformation behaviour and material failure in lattice structures, even when the lattice topology was held constant. The study in this paper focused on three topologies, BCC, BCCZ, and FCCZ, each printed in three orientations, i.e., XY, YZ, XZ. Another process-specific parameter involves *manufacturing deviations*, which include geometric and material deviations inherent to the SLS process. These deviations were studied primarily in Paper C, which showed that thin struts often deviate from their nominal design in shape, cross-section, and diameter, leading to substantial changes in mechanical response relating to stiffness and compressive strength. Material deviations were also found to affect flexibility, such as reduction in E of as-printed material compared to the base material as presented in Paper C.

These observations were further reinforced by the findings in Paper D, which demonstrated that incorporating manufacturing deviations alongside geometry-specific parameters enabled accurate prediction of strut-level mechanical response; thus, highlighting the interdependence of geometric- and process-specific parameters. The deviations remained significant at the lattice level as well, as seen in Paper E, affecting the predictive accuracy of numerical simulations, which further emphasised the importance of accounting for manufacturing realities into the design process

In summary, Papers B to E collectively demonstrate that lattice geometry (i.e., lattice size and topology, strut diameter, and strut orientation), printing orientation, and manufacturing deviations are the influencing factors in designing flexible lattice structures. However, achieving a more complete view of flexible lattice structure design requires further exploration of other potential factors, for instance, those highlighted in Paper A.

- *RQ3: How can a simulation-driven design approach be developed and applied to integrate influencing factors in the design of flexible lattice structures for additive manufacturing?*

Addressing the development part of RQ3, this thesis developed an SDD approach to integrate geometry-specific and process-specific parameters into the design process of flexible lattice structures. This approach, centered on DDfAM, is formalised in Paper E and presented in Figure 20. It systematically integrates geometric design, material behaviour, and manufacturing constraints into a calibrated numerical model, explicitly accounting for as-printed conditions to improve predictive accuracy.

The approach builds on empirical insights from Papers C and D, which quantified the effects of strut diameter, strut orientation, and manufacturing deviations on Young's modulus, E, of as-printed material, and in Paper E, which showed how these strut-level parameters influence the mechanical behaviour at lattice level. The SDD approach is organised around four key elements, as discussed in the next paragraphs.

The first key element of the approach involves *incorporation of geometry-specific parameters* through lattice definition. These include lattice topology, strut diameter, strut orientation, and lattice size, which collectively govern both strut-level and/or lattice-level mechanical responses. At the strut-scale, Paper D demonstrated that variations in strut diameter and orientation directly influence E of the as-printed material in thin strut-based structures, establishing an empirical relationship, with strut orientation having a dominant effect. At the lattice scale, Paper E confirmed that lattice topology and lattice size further shape the global mechanical behaviour. This paper demonstrated that careful integration of all of the above-mentioned geometry-specific parameters facilitates the design of flexible lattice structures, as evidenced by the five lattice variants generated in Paper E, to replicate the stiffness of conventional materials, specifically PUR foams used in furniture upholsteries.

The second key element involves manufacturing consideration, i.e., *incorporation of process-specific parameters* which account for manufacturing realities in SLS processes. Paper C identified that 3D printed thin struts exhibit geometric deviations, such as tapering, elliptical cross-sections, and average deviations in strut diameters, as well as material deviations, such as reductions in as-printed material stiffness. Both types of deviations were found to significantly affect mechanical behaviour of the printed structures.

Further, building on the measurements and modelling principles from Paper D, geometric deviations were calculated as strut diameter offsets and average diameter deviations, to be used in Paper E. Similarly, material deviations identified at strut level in Paper D were introduced as a material model for conducting simulations in Paper E, thus applying these deviations at lattice level.

The third key element involves *numerical modelling and calibration*. An initial numerical model was developed in Paper C to account for manufacturing deviations observed in 3D-printed test artefacts and was calibrated against experimental results. Building on the modelling principles established in Paper C, Paper D developed a numerical model at the strut level, specifically targeting bending-dominated structures. Paper E subsequently built on this model by incorporating calibrated strut-level material properties into a beam-element FE model and extending its application to the lattice level using nonlinear structural analyses in Karamba3D.

Geometric deviations were integrated into the numerical model in Paper E, through explicit geometry modifications in CAD model to include strut diameter offset mentioned previously. Additionally, average diameter deviations were implemented as nodal perturbations within the beam-element model. By embedding these quantified geometric variations directly into the numerical model, the SDD approach ensures that simulation outputs reflect not only idealised designs but also realistic manufacturing conditions.

Calibration constitutes a critical step in the SDD approach. In Paper D, parametric optimisation was employed at the strut level to calibrate E values as a function of strut diameter and orientation. This calibration enabled the prediction of E across different lattice configurations. The resulting calibrated material properties were then assigned to individual struts within a lattice-level numerical model in Paper E, enabling prediction of global mechanical behaviour. This hierarchical integration enabled the extrapolation of strut-level behaviour to full lattice structures. By incorporating the characteristics of the as-printed parts, the numerical model improves prediction accuracy and bridges the gap between as-designed and as-printed mechanical performance.

The fourth key element is the *iterative SDD loop*, detailed in Paper E. The predicted mechanical response obtained from the numerical model is used to guide iterative manual or optimisation-driven adjustments of geometric parameters within this loop. This closed-loop process continues until the target mechanical response is achieved, enabling systematic refinement of lattice geometry toward the desired flexibility.

Answering the application part of RQ3, Paper E validated the proposed SDD approach at lattice level by implementing it to develop variants of flexible lattice structures. These variants were based on Kelvin cell topologies with differing strut diameters and scaling factors, designed to replicate the mechanical behaviour of reference PUR foams with varying stiffnesses, commonly used in furniture upholstery. Through the iterative SDD loop (refer Figure 20), lattice parameters were adjusted until the target pressures were achieved, producing five lattice design variants. Validation showed that numerical predictions closely matched experimental measurements, confirming the predictive accuracy of the approach within the broader framework presented in the paper.

Further product-level validation was demonstrated in Paper E by integrating one of these design variants to create a flexible lattice structure intended to replace the original PUR foam in a cushioned headrest for office chairs. The successful implementation as a headrest prototype highlighted the scalability of the approach and confirmed its practical relevance in real-world applications.

In summary, the SDD approach developed in this thesis systematically integrates both geometry-specific parameters (lattice topology, strut diameter and orientation, lattice size) and process-specific parameters (printing orientation and manufacturing deviations) into a calibrated numerical model. Papers C to E collectively demonstrate that this integrated approach enables the design of flexible lattice structures while providing accurate predictions of their mechanical behaviour. Although the current approach has been validated for SLS-printed PA 1101 lattices, its underlying principles could be extended to other materials, lattice topologies, and AM processes in future studies, broadening its relevance within DDfAM.

5.2 Conclusions

The research presented in Papers A to E collectively advances the design of flexible lattice structures for AM. Based on these studies, this thesis establishes six key conclusions regarding the design, prediction, and practical implementation of such structures.

First, a DDfAM perspective is essential, requiring the simultaneous consideration of geometric design and manufacturing realities.

Second, both geometry-specific parameters (lattice topology, strut diameter and orientation, lattice size) and process-specific parameters (printing orientation, manufacturing deviations) jointly determine mechanical behaviour and must be integrated into the design process.

Third, an SDD approach can effectively embed these parameters, enabling accurate prediction of mechanical responses for the intended flexible lattice structures.

Fourth, multiscale inevestigation at strut-, lattice- and product- levels is crucial for ensuring reliable and transferable performance.

Fifth, the SDD approach is scalable and applicable to real components, as demonstrated by the successful integration of a lattice design into an office chair headrest.

Finally, flexible lattice structures benefit from an integrated approach that links design, manufacturing, and evaluation, allowing tighter coupling of numerical and CAD modelling, experimental insights, and process considerations. Together, these conclusions provide a structured pathway for designing tunable, and functional flexible lattice structures, advancing the field of DDfAM.

6 Research contributions, limitations and future work

This chapter outlines the research contributions, highlights any research limitations, and provides suggestions for future research.

6.1 Research contributions - Contributions to theory

The presented research makes several theoretical contributions that advance knowledge at the intersection of DDfAM, SDD, and lattice structure design.

6.1.1 SDD approach centered on DDfAM

An SDD approach was developed in this thesis to support the creation of flexible lattice structures specifically designed for AM. The approach incorporates data from geometric and material characterisation of as-printed structures directly into the numerical model. By embedding these manufacturing-informed parameters, discrepancies between as-designed and as-printed mechanical performance, commonly reported in existing literature [186], are significantly reduced. Moreover, unlike prior studies that have treated FE-based simulation approaches, manufacturing deviations, or calibration methods in isolation [42, 70], the proposed approach combines these elements together to enable controlled mechanical response for functional applications. Additionally, it addresses the existing gap of limited integration among FEA, CAD, and optimisation within a unified environment for lattice structure design by explicitly linking FE-based simulations with CAD modelling and incorporating design optimisation into the same. This gap has been reported in Paper A and discussed while answering RQ1 in Section 5.1.

Moreover, in this approach, virtual predictions are systematically combined with physical experiments, allowing simulation results and experimental findings to continuously inform one another and refine the model. This iterative refinement provides deeper insights into material behaviour, process limitations, and the real mechanical performance of 3D-printed lattice structures.

Further, while extensive research has focused on lattice structures for stiffness and lightweight applications, this thesis addresses the comparatively underexplored objective of structural flexibility. In this context, the developed SDD approach specifically facilitates the design of flexible lattice structures.

6.1.2 Geometry-driven flexibility

This research extends literature concerning mechanical metamaterials, specifically focusing on lattice structures by demonstrating that structural flexibility can be achieved through strategic geometric design using traditionally stiff materials, rather than relying solely on material softness. The work establishes that lattice topology, strut thickness and orientation, and lattice size can be strategically varied to achieve flexibility without depending on inherently soft elastomeric materials. This theoretical contribution broadens the range of materials for flexible structures to even include stiffer bio-based polymers like PA 11, highlighting how material selection and geometric design interact in achieving desired mechanical behaviour.

6.1.3 Multiscale design of lattice structures

Empirical relationships between strut-level parameters (diameter, orientation) and mechanical behaviour of as-printed materials were established through a combination of experimental and numerical investigations. These relationships then formed the basis for estimating mechanical behaviour at the lattice level. In this way, the research shows how geometric and material properties propagate from individual struts to full lattice structures, extending also to product-level components, providing a foundation for designing tunable metamaterials, more specifically flexible lattice structures. This multiscale insight can support controlling mechanical behaviour by adjusting key lower-level design parameters.

6.1.4 Integration of manufacturing realities into design processes

This work challenges the conventional reliance on idealised CAD models by developing an approach that incorporates as-printed material characteristics, including geometric deviations and material property variations, directly into the design process. The layer-by-layer nature of AM leads to differences between as-designed and as-printed materials, and this research addresses that gap by treating manufacturing deviations as process-specific parameters to be incorporated into the design, for instance, in the form of design tolerances in the CAD model. This approach reinforces the view of simulation not merely as a post-design validation tool, but as an integral part of the engineering design process.

6.1.5 Classification and mapping of DDfAM research landscape

Through a systematic literature review, this thesis provides a comprehensive mapping of the DDfAM research landscape, organising it into key research areas and highlighting existing design strategies that support its implementation across the engineering design process. The work addresses the previously fragmented state of DDfAM research and identifies critical gaps, particularly the limited integration of SDD approaches with DDfAM for designing lattice structures when aiming for structural flexibility. This classification offers a structured basis for assessing how current design strategies contribute to lattice structure design and where future research efforts are needed.

6.2 Research contributions – Contributions to practice

The presented research makes several practical contributions that address real-world challenges in sustainable manufacturing, product development, and industrial implementation.

6.2.1 Sustainable material alternatives for industry

This work demonstrates how bio-based polymers, specifically PA 1101 (a castor oil-derived polyamide), can work towards replacing environmentally harmful petroleum-based materials such as PUR foams, typically seen in furniture upholstery and similar applications. By focusing on sustainable materials with improved recyclability and lower carbon footprints, this research directly supports the transition toward more environmentally responsible manufacturing practices aligned with the SDGs of the United Nations. The approach addresses growing industrial interest in bio-based polymers while aiming to maintain functional performance requirements. Although such biopolymer-based structures cannot yet fully replace low-cost PUR alternatives, they can function as bio-based alternatives that contribute to a more sustainable solution.

6.2.2 Practical design tools

The SDD approach developed in this research can be directly applied by practitioners when designing flexible lattice structures for SLS process. The approach involves designing parameterised test artefacts for material and geometric characterisation, calibrating numerical models that account for manufacturing deviations, continuously refining and validating simulations through experimental comparison, and an iterative design loop. In this way, the implementation of the approach can reduce the trial-and-error way, traditionally required in design involving AM, saving development time, material consumption, and associated costs.

6.2.3 Demonstrated scalability from laboratory to product

Scalability was demonstrated from laboratory-scale specimens to real-world component through a furniture headrest case exemplification conducted in collaboration with industry partner, JI – a Sweden based furniture company. The demonstrator prototyped as part of the thesis shows practitioners how the developed SDD approach can be transferred to actual commercial applications. The case component exemplifies that the approach developed in this thesis can be applied beyond controlled laboratory conditions and can potentially handle the complexities of real product requirements, though experimental validation of the full-scale component remains part of future work that would further substantiate the industrial applicability of the design approach.

6.2.4 Expanded application domains

This research opens new possibilities for 3D-printed flexible lattice structures across multiple industries, with the added advantage of explicitly incorporating a DDfAM perspective in the design process. Potential application areas include robotics (locomotion systems), healthcare (foot orthotics and prosthetics), aerospace (adaptive aircraft components), protective equipment (cranial helmets and padding), and furniture (ergonomic upholstery). By demonstrating how traditionally stiff materials can achieve flexibility through geometric design, the work expands the design space available to practitioners and enables new product innovations across these diverse sectors.

6.2.5 Improved product quality and manufacturing reliability

By accounting for manufacturing deviations and process-induced variations during the design phase rather than after production, this research can lead to higher-quality, more reliable, and better manufacturable AM products. The issue becomes particularly pronounced when lattice features such as strut size approach the lower limits of manufacturability, where process-induced variations significantly affect performance. Addressing these variations in design reduces the risk of build failures, dimensional inaccuracies, and performance inconsistencies, thereby improving the overall adoption of AM technologies in production environments.

6.2.6 Reduced development costs, material usage and environmental impacts

By narrowing the gap between as-designed and as-printed part performance, fewer build-test iterations are required. This directly lowers prototyping time, machine and material usage, validation efforts, and costly redesign loops caused by performance mismatches. In addition, lightweight lattice structures reduce the amount of material needed while maintaining required performance, which lowers waste generation by minimising excess material use and scrap. This material efficiency not only reduces waste but also promotes more sustainable manufacturing practices and enhances the economic viability of bio-based materials like PA 1101, used in this research. Furthermore, the ability to design functional structures using such sustainable materials directly supports the industrial transition toward more environmentally responsible practices, addressing sustainability challenges associated with fossil-based elastomeric materials.

6.2.7 Circular economy and broader design implications

This thesis primarily focuses on the structural flexibility, manufacturability, and material robustness of additively manufactured flexible lattice structures; however, the findings also extend to broader design implications. Geometry-driven flexibility enables mono-material designs, simplifying material streams and facilitating end-of-life processing (for instance, sorting, handling, recycling) without relying on elastomeric or multi-material compositions. Additionally, lattice-based structures allow material to be placed precisely where it is needed, reducing overall material usage, and potentially weight, without necessarily compromising performance. Furthermore, the combination of AM and SDD enables on-demand, application-specific production of parts. Early integration of SDD also supports trade-offs between performance, material use, and manufacturing considerations, supporting better design decisions concerning the design of flexible lattice structures. This is particularly relevant in design contexts where environmental impact and resource efficiency are increasingly important drivers.

6.2.8 Knowledge transfer and industry - academia collaboration

Through the STEPS project and close collaboration with Swedish furniture companies, this thesis demonstrates effective knowledge transfer between academia and industry. This contribution helps bridge the existing gap between theoretical research and practical application, supporting wider adoption of sustainable AM practices in manufacturing. The collaborative approach ensures that research outcomes are aligned with real industrial needs and constraints, however, there is a need for full scale industrial case implementation to validate these outcomes.

6.3 Limitations and future research

This thesis has explored the potential for extending DfAM to the design of flexible lattice structures. While the work offers valuable insights, certain limitations remain. Moreover, continued investigation will be essential to develop a more comprehensive and practical design approach. The following sections outline the key limitations and some suggestions for future work.

6.3.1 Extending numerical modelling

- ***Extending the model to capture nonlinear and failure behaviour***

Centered on DDfAM, this thesis presented an SDD approach, the core of which involves numerical modelling to effectively capture the mechanical response in linear elastic region. The modelling is based on elastic–perfectly plastic material assumptions, limiting its applicability to response prior to the onset of plastic deformation. Future work could extend this framework by introducing more sophisticated material models capable of capturing nonlinear behaviour, including plastic deformation, and associated effects related to crumpling and energy absorption as well as fatigue. Such developments would enable the simulation of a wider range of loading conditions, improving predictive capability under complex or repeated mechanical loading. Extending the model to account for multiple load cases would further enhance its predictive capability and relevance to practical applications.

- ***Strengthening predictive capability through expanded experimental data***

The statistical robustness and predictive accuracy of the approach could be further enhanced through larger and more diverse experimental datasets. Increasing the sample size would help capture the variability inherent in the manufacturing process; while employing advanced statistical or machine learning techniques could improve the ability of the model to deal with complex scenarios involving several interdependent parameters (i.e., higher-dimensional parameter spaces). These approaches would contribute to a more generalisable and reliable predictive model.

- ***Improving the representation of as-printed geometry***

The numerical model considers geometric deviations through average variations in strut diameter, which provides a simplified description of the as-printed material. Future research could adopt µCT scanning or 3D surface reconstructions to capture localised geometric imperfections, including variations in surface roughness or form deviations. Accounting for these variations would provide a more physically realistic representation of printed structures, improving accuracy and fidelity of the predicted mechanical properties.

- ***Incorporating process-specific information into the numerical model***

Finally, future research could also focus on extending the numerical model to incorporate process parameters obtained through in-situ monitoring or data acquisition during printing, using techniques such as thermal imaging or layer-wise optical scanning.

6.3.2 Towards automated design optimisation

In the presented work, the design optimisation of flexible lattice structures was performed manually, iterating design parameters such as strut diameter and lattice size, alongside manufacturing constraints like printing orientation, to achieve the desired structural flexibility. This was guided by performance indicators, such as the difference in force response relative to target materials' (e.g., foams) at specific deformation load-steps or comparing the Young's modulus of the as-printed materials to target values. Future research could focus on developing an automated approach facilitating design optimisation that integrates the predictive numerical model presented in this thesis. Such an approach would enable exploration of multiple design parameters and manufacturing constraints, iteratively adjusting them to achieve target structural flexibility. Automating this process would facilitate the generation of new design concepts, support the selection of optimal lattice configurations, and enable more informed decision-making to achieve desired performance outcomes.

6.3.3 Engaging SDD with artificial intelligence (AI)/ machine learning (ML)

Although in the presented work, AI/ML capabilities are not explored, their increased use in today's world makes it plausible to have been integrated with SDD; however, the real impact will depend on how effectively AI/ML is used to accelerate iterations and support decisions when there is uncertainty in materials, manufacturing, and modelling.

- ***Using ML surrogates for earlier and faster exploration of designs***

One practical direction is to build hybrid SDD approaches where physics-based FE models remain the main reference for correct behaviour, while ML models serve as fast surrogates during design exploration. This would make it possible to quickly screen design sensitivity and compare concepts (e.g., mapping topology, strut diameter, orientation, and scaling to mechanical responses) before spending time on high-fidelity simulations or printing.

- ***Enabling SDD through inverse design and uncertainty quantification***

Another step is to use AI/ML for inverse design, meaning the model does not only predict performance, but also suggests lattice parameter sets that achieve a target response (such as foam-like behaviour) while still satisfying manufacturing constraints. In parallel, adding uncertainty quantification would make the workflow more robust by accounting for manufacturing deviations, material scatter, and modelling assumptions, so designs can be chosen based on confidence rather than a single best estimate.

- ***Defining and validating the limits of AI/ML-supported predictions***

If AI/ML is introduced, performance alone would not be enough as results must also be trustworthy. This requires a) explainability, so predictions can be interpreted in appropriate engineering terms (which parameters drive changes and why), b) traceability, so data sources and model versions are clearly documented and results can be audited and reproduced, and c) generalisability, so the 'domain of validity' of the model is defined and verified through stepwise validation: from small, simple changes to larger shifts across parameter ranges, materials, and processes with recalibration when necessary.

6.3.4 Broadening material and process applicability

The studies presented in this thesis are limited to a single material, i.e., bio-based plastic, PA 1101, manufactured using SLS technology. To enhance the generalisability of the presented SDD approach, future studies could adapt and validate the research outcomes for a broader range of materials, including other bio-based plastics, extend the applicability to alternative AM technologies such as fused filament fabrication or stereolithography. Such extensions would promote broader applicability across different AM technologies and design contexts. However, challenges remain in sourcing commercially available bio-based plastics, especially suitable for SLS printing, as many materials appropriate for flexible lattice structures are still limited to specialised material laboratories and are not produced at large scale.

6.3.5 Performing scale-up studies within industries

While one of the studies in this thesis provides a case exemplification involving full-scale prototyping to demonstrate the validity of the proposed numerical model, future work could focus on performing large-scale tests in an industrial setting. Such scale-up studies would refine the presented numerical model, validate its predictive capability at larger scales, and assess the feasibility of applying the findings to real-world applications, thus, supporting broader implementation of bio-based, additive-manufactured flexible lattice structures.

Successful adoption in industry would require evaluating the SDD approach within operational contexts, considering manufacturability, performance under application-specific loading, and material availability. Engaging with industrial users to test usability of the proposed approach in their specific settings would further ensure that the outcomes are practical and widely acceptable.

6.3.6 Exploring broader design implications of flexible lattice structures

While this thesis primarily focuses on the structural flexibility, manufacturability, and material robustness of additively manufactured lattice structures, it also highlights broader design implications, as outlined in the research contributions. Future research should therefore aim to validate and quantify these implications across a wider range of applications, materials, and manufacturing conditions to assess their robustness and general applicability.

- ***Advancing sustainability and circular economy benefits***

In particular, comparative studies on recyclability, material recovery, and reuse between bio-based flexible lattice structures and conventional flexible materials would help strengthen the circular economic relevance of this work. Lifecycle assessment studies could further clarify differences in environmental impact across production, use, and end-of-life stages.

- ***Advancing material efficiency, durability, and practical adoption***

Future work should also quantify material and weight savings enabled by geometry-driven lattice design and examine how combining AM with SDD support on-demand production, improved durability, and extended product lifetimes. Additionally, long-term durability and fatigue behaviour should be evaluated through real-world testing at product level and even at system levels to better support the adoption of flexible lattice structures in wider product development contexts.

6.3.7 Extending applicability beyond AM

Although this thesis is grounded in DDfAM and SDD for flexible lattice structures, several findings have broader relevance as they demonstrate how geometry can be leveraged to tailor mechanical behaviour and how predictive models can be calibrated across scales: from struts to lattices and towards product-level use. Future work could therefore explore how the research outcomes presented in this thesis can be translated to adjacent research fields and industrial domains.

- ***Extending geometry-based flexibility to other application domains***

A first direction could be to investigate application areas where controlled flexibility is a primary function and where material substitution (e.g., reducing reliance on foams or elastomers) is desirable. Examples include compliant mechanisms and soft robotics components, biomedical cushioning and orthotics, impact protection and energy-absorbing structures, and packaging for secure transportation of fragile products, where predictable force-displacement response is critical and manufacturability constraints strongly influence real performance. In such contexts, the thesis' focus on geometry-driven flexibility and calibration using as-printed characteristics is particularly relevant, because these products are often sensitive to small geometric and material variations that shift stiffness and failure behaviour.

- ***Adopting 'dual' design thinking beyond AM***

A second direction is more methodological and involves generalising the 'dual' design logic as the core design concept for manufacturing processes where performance and manufacturability are tightly coupled. Future research could evaluate whether the DDfAM-based research outcomes presented in this thesis, such as early identification and integration of key constraints, the design of parameterised test artefacts, calibrated predictive models, and an iterative experimental-numerical refinement loop, can be transferred to design and manufacturing contexts beyond those investigated here.

Declaration on the use of generative artificial intelligence

In preparing this thesis, the author used generative AI tools only for language-related assistance, such as improving clarity, style, and formatting text. No such tools were used for the generation of scientific content or intellectual contributions.

The author retains full intellectual ownership of this work and accepts complete responsibility for its content.

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