Solid Freeform Fabrication 2024: Proceedings of the 35th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

BENCHMARKING THE CURRENT STATE OF LATTICE DESIGN SOFTWARE FOR ADDITIVE MANUFACTURING

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ABSTRACT

The increasing potential of additive manufacturing has been a catalyst for the adoption of lattice structures in design. Lattices are characterized by their light weight and high strength-to-weight ratio and have thus found use in industries like automotive, aerospace or medical where these attributes are useful. For this purpose, a number of lattice design software tools have emerged, aiming to enable the full power of lattice structures. Even with these software tools, applying a lattice to a component can be a complicated task due to its high complexity and the numerous approaches available. However, these software packages do facilitate the lattice design process and also ensure accuracy and reliability. Indeed, lattice structures find applications in various industries that demand precision and meticulous control over properties. This paper aims to provide an overview of the current landscape of lattice design software, with a particular focus on eight prominent platforms. Throughout the study, each software's features and functionalities were examined, shedding light on the main shared and distinguishing characteristics. Several notable patterns emerged during the analysis, revealing significant overlaps between certain software offerings. This observation suggests a shared goal among these platforms, wherein they strive to address common challenges and meet the same objectives in lattice design.

1. Introduction

Lattice structures, hailed for their unique properties, have become a cornerstone in various structural design applications due to their exceptional characteristics such as high strength-to-weight ratio, lightweight properties, efficient heat transfer, and customizable porosity and grading [1]. These cellular structures, formed by repeating patterns intricately connected to form three-dimensional entities, find application in an ever-expanding array of fields. Research on lattice structures continues to evolve, discovering new ways to optimize their properties and thereby broadening their scope of utilization.

One of the standout benefits of lattice structures is their contribution to sustainable manufacturing by significantly reducing material usage and waste [2]. In engineering domains like automotive and aerospace, where strength and lightweight attributes are paramount, lattice structures emerge as alternative solutions to solid materials [3]. Despite the proven reliability of solid materials, lattice structures, with their unique characteristics, better align with the stringent requirements of these fields.

Another standout benefit of lattice structures is their versatility, as engineers can tailor them to meet specific requirements. The ability to generate lattice structures from heterogeneous unit cells and customize parameters such as width and size grants engineers unprecedented control over the materials they create. However, the design of lattice structures is not without its challenges. The complex arrangement of unit cells necessitates sophisticated computational tools, often requiring powerful computers even to visualize the full lattice assembly [4]. Evaluating the properties of these intricate structures is also a demanding task, primarily addressed through the use of specialized software, machine learning techniques, or physical testing [5–7]. The increasing prevalence and complexity of lattice structures have given rise to highly specialized lattice design software, providing essential assistance in product development involving lattice components. Such software packages effectively enable designers to take full advantage of the versatility and customizability of lattice structures.

As the potential of lattice structures continues to grow and their applications diversify, the choice of lattice design software becomes a pivotal factor. Each software, with its unique interface and implementation of lattice features, plays a crucial role in transforming conceptual ideas into tangible lattice components. The objective of this research is to shed light on the current state of lattice design software packages, offering insights into their capabilities and, notably, undertaking a comparative analysis of the diverse features they bring to the table. Through this exploration, we aim to provide a comprehensive understanding of the landscape of lattice design software, aiding engineers and researchers in making informed decisions regarding their choice of software for lattice structure development. This work also serves to help developers identify the path forward for next generation lattice design software packages.

The remainder of the paper is organized as follows. Section 2 provides a brief background, introducing key terms and definitions related to lattices and reviewing research that has applied lattices in the realm of AM. Section 3 describes the methodology used to compare a set of leading lattice design software packages. Section 4 discusses the comparison, highlighting areas of commonality, uniqueness, and innovation. Finally, Section 5 concludes the paper with a summary of key results, limitations, and directions for future work.

2. Background and related work

2.1 Lattice Definitions and Terminology

In the process of lattice design, the selection of the lattice type holds paramount importance, as each type presents distinctive properties. Nearly every lattice structure falls into one of three main categories: periodic lattice structures, randomized lattice structures, and pseudo-conformal lattice structures. Periodic lattice structures are formed by replicating a unit cell across all three dimensions. This structure can be either homogeneous, characterized by a uniform unit cell, or heterogeneous, with unit cells varying in size along the geometry. In contrast, randomized lattice structures are composed of unit cell sizes and nodes which are distributed randomly throughout the 3D mesh. Finally, pseudo-conformal lattice structure involves cells with the same topology but potential variations in shapes or sizes [8–10].

Among these types, periodic structures tend to be the most commonly employed. This category contains strut-based lattices (see Figure 1), consisting of rod-like forms connected in different orientations to create various unit cells within the lattice structure. This category also contains Triply Periodic Minimal Surfaces (TPMS) structures (see Figure 2), which are complex surfaces defined by equations. The gyroid lattice is one of the most notable and recognizable TPMS lattices. Conforming TPMS structures to freeform surfaces is still a struggle for most solutions, but by using mesh surface conformal parameterization and a novel geometric structure, TPMS units can adapt to various surface shapes [11]. Planar-based lattices represent another approach, crafted as a periodic pattern on a 2D plane and then extruded in a single direction to yield a 3D structure. This lattice type shows one of a kind properties due to its unique shape, such as having zero Poisson's ratio over large deformations [12].

Furthermore, the design and the symmetry of this structure enables efficient creation of lattice structures with functionally graded properties [13].

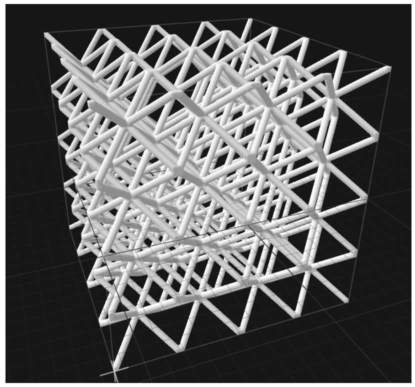

Figure 1: Strut based lattice

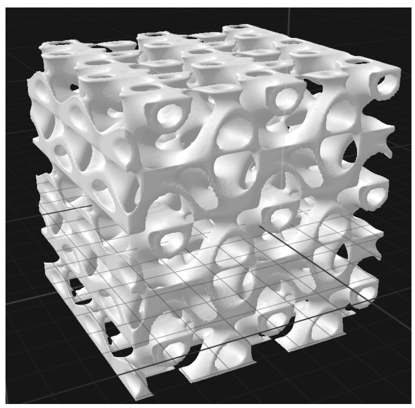

Figure 2: TPMS lattice

Stochastic lattices and pseudo-conformal lattices see relatively less use. For applications requiring isotropic properties, stochastic lattices come into play, where cells are randomly connected throughout the global structure. For instance, a Voronoi structure has strong characteristics [14]. Pseudo-conformal lattices can be useful when the surfaces of a part are expected to experience intense loading, but are challenging to design. Additionally, different lattices can be combined together to form a multi lattice. Transition regions can be automated using various methods [15,16].

In short, a multitude of lattice structures are available in additive manufacturing, each offering unique customization and modeling possibilities [17].

2.2 Prior Research on CAD for Lattices

Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) software enables real-time analysis of digital design, which can help reduce time spent in creating and testing physical prototypes [18]. While a considerable amount of previous research has been conducted on computer-aided design (CAD) software [18–21], much less research exists on lattice design software. The work that does exist aims to elucidate the aspects of lattice design within the context of design in additive manufacturing (AM) [22]. In fact, AM is often seen as a crucial tool for making personalized products and it offers a lot of flexibility in the design process. It allows for creative and customized designs, making it easier to create products that suit special needs [23,24]. CAD software has been proven to have great potential, allowing engineers to save time, money and efforts [25]. Furthermore, the integrated CAD/CAE package identifies and corrects flaws, showcasing the efficiency of these software tools in accelerating product development [26]. As for the link between CAD software and the progress in additive manufacturing, current research is exploiting the capabilities of additive manufacturing to address evolving requirements in high-performance engineering systems. This reinforces the belief that CAD software plays a crucial role in exploiting the full potential of additive manufacturing [24]. This paper aims to provide an overview of the current landscape of lattice design software packages, highlighting their comparative strengths and differences.

3. Methodology

This work conducts a comparison of lattice design software packages. This is based on an in-depth examination of the full licenses of each software, aiming to gain a comprehensive understanding of their features and functionalities. Each software underwent a meticulous analysis, with a focus on exploring and documenting individual features to ensure accuracy in the assessment of design capabilities.

3.1 Software considered in this work

For the purposes of this work, a sample of eight software packages was chosen. These software packages were selected based on prevalence in the market, feature completeness, and supporting documentation. These packages exhibit a variety of similarities as well as drastic differences. The remainder of this section briefly introduces each software with a screenshot of its primary interface.

Altair Inspire (see Figure 3) is a powerful software designed for engineers and designers to create and optimize lattice structures. With its user-friendly interface and advanced features, Altair Inspire enables users to conduct detailed simulations and refine lattice designs with ease.

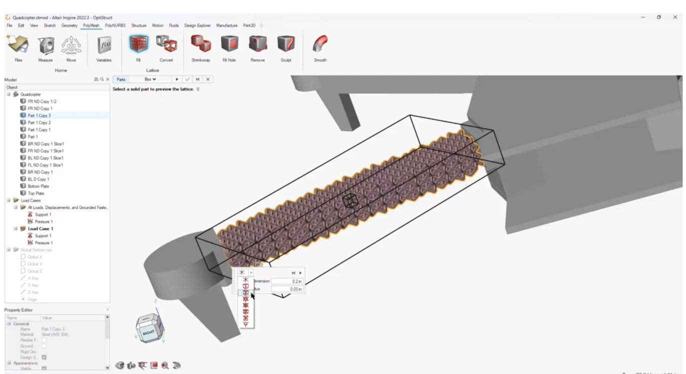

Figure 3: Graphical User Interface for Altair Inspire[1]

[1] https://altair.com/inspire

Carbon Design Engine (see Figure 4), is a 3D printing software employing digital light synthesis technology. It enables users to design and produce precise lattice structures, particularly within the context of additive manufacturing for various industries.

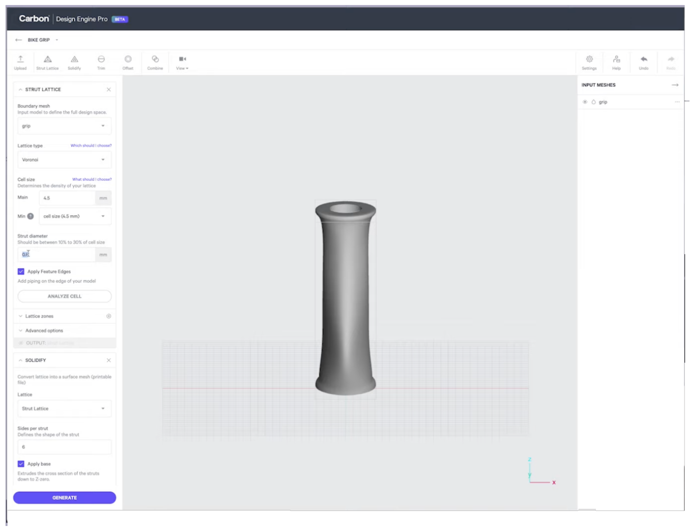

Figure 4: Graphical User Interface for Carbon Design Engine[2]

Autodesk's Fusion 360 (see Figure 5) is a versatile CAD/CAM software with lattice design capabilities. This collaborative tool integrates design and manufacturing processes, allowing users to create intricate lattice structures efficiently.

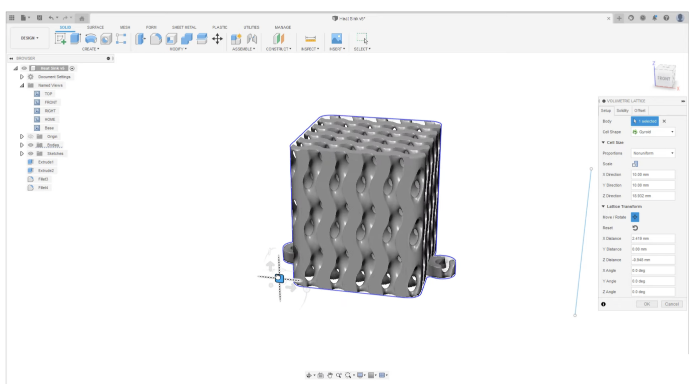

Figure 5: Graphical User Interface for Fusion 360[3]

Shown in Figure 6, Materialise 3-matic is a versatile lattice design software developed by Materialise, a leading provider of 3D printing software and services. This software is specifically designed for advanced 3D modeling and mesh processing, offering a range of features that cater to various applications, including lattice structure design. This software is widely used in health science.

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[2] https://www.carbon3d.com/products/carbon-design-engine

[3] https://www.autodesk.com/products/fusion-360/overview

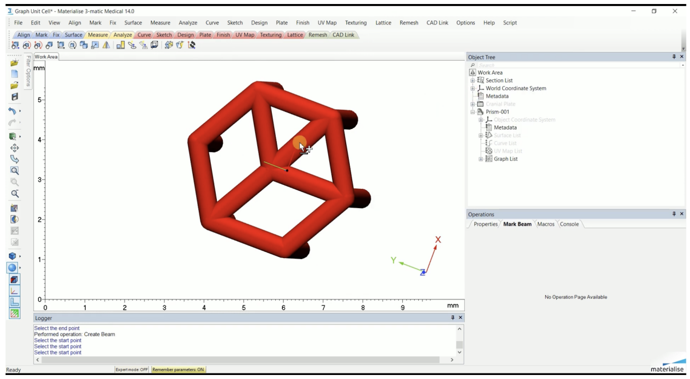

Figure 6: Graphical User Interface for Materialise[4]

Metafold 3D, seen in Figure 7, focuses on creating advanced geometries and structures. It aims to provide a user-friendly platform for designing intricate lattice patterns, applicable in areas such as architecture and product design.

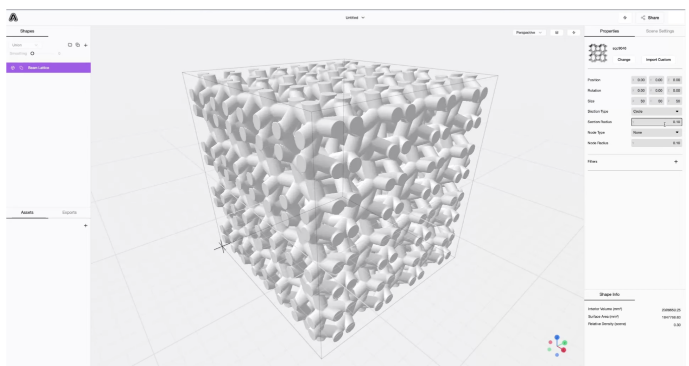

Figure 7: Graphical User Interface for Metafold 3D[5]

Figure 8 shows the next software package, nTop. nTop is known for its advanced engineering capabilities in lattice design. It empowers engineers to efficiently create complex structures, offering tools for optimization, simulation, and seamless integration into existing workflows.

[4] https://www.materialise.com/en/industrial/software/3-matic

[5] https://www.metafold3d.com/

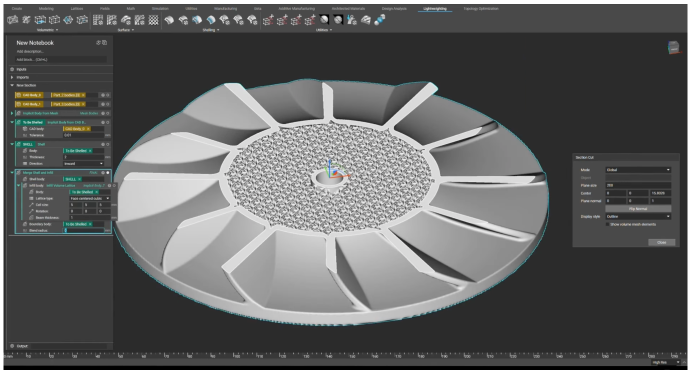

Figure 8: Graphical User Interface for nTop[6]

Ultrasim3D by BASF (see Figure 9) provides 3D printing solutions along the entire Additive Manufacturing value chain, under the brand Forward AM.

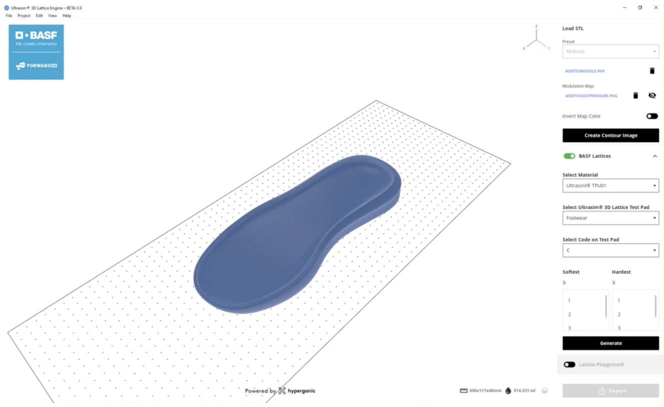

Figure 9: Graphical User Interface for Ultrasim3D[7]

Siemens NX, a comprehensive CAD/CAM/CAE software from Siemens Digital Industries Software shown in Figure 10, has a long history of continuous updates. It includes lattice design features, aiming to provide a complete solution for product design, engineering, and manufacturing, with advanced tools for creating and optimizing lattice structures.

[6] https://www.ntop.com/
[7] https://forward-am.com/service-portfolio/ultrasim-3d-software/ultrasim-3d-lattice-engine/

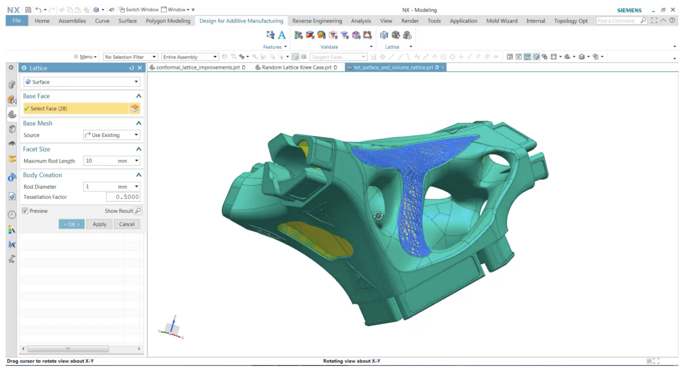

Figure 10: Graphical User Interface for Siemens NX[8]

The selection of eight different lattice design software packages for this study was carefully considered to ensure the sample's representativeness and relevance. The chosen software packages encompassed a variety of popular options from different editors, each with contrasting release dates.

We examine this set of software packages from three distinct perspectives. First, a benchmarking study is performed to compare the basic features of each software package. Second, we elucidate the working mechanisms of each software as unique workflows. Workflows play a crucial role in engineering design by offering structured frameworks for managing tasks and projects effectively. Finally, we provide a discussion of the unique features present in each software package.

4. <u>Results and Discussion</u>

The analysis will be presented in different categories, starting by comparing basic features of the software packages, continuing by analyzing workflows, and finishing by exploring advantageous features that are implemented in these software packages in order to excite the user’s experience.

4.1 <u>Comparison of Basic Features</u>

Upon initial inspection, several of these software interfaces appear similar. Ultrasim3D, Carbon, and Metafold 3D exhibit resemblances, as do Siemens NX, Fusion 360, and Materilise 3-matic. However, a quick evaluation of the interface barely scratches the surface, providing a visual comparison without diving into the software's functionality and capabilities. A deeper analysis is necessary to uncover the differences and unique features that distinguish each software, allowing for a better understanding of their respective strengths and limitations.

It is pertinent to initiate a comparison of the lattice features in order to evaluate the performance of each software in this aspect. To facilitate this evaluation of lattice type availability, lattice features, and other important criteria, a benchmarking table is presented (Table 1). Additionally, clarity on the terminology used is essential. In lattice structures, *grading* denotes a variation of the unit cell’s struts size along a direction, as well as controlled modification of the unit cell size. Moreover, an *offset* feature allows users to shift, scale, or modify the lattice structure, providing flexibility for specific applications, improve performances, or meet customization requirements.

[8] https://plm.sw.siemens.com/en-US/nx/

Table 1: Basic Feature Comparison

	Software	Altair Inspire	Autodesk Fusion	Carbon Engine	Hyperganic	Materialize 3-matic	Metafold	nTopology	Siemens NX
Lattice type availability	Customized Lattice	✓	✓	✓	✓	✓	✓	✓	✓
	TPMS Structure	✓	✓	✓	✓	✓	✓	✓	✓
	Strut-Based Lattice	✓	✓	✓	✓	✓	✓	✓	✓
	Planar Lattice	✓	✓	✓	-	✓	-	✓	✓
	Stochastic Lattice	✓	-	✓	-	✓	-	✓	✓
Lattice features	Grading	✓	✓	✓	✓	✓	✓	✓	✓
	Conformal Lattice	✓		✓	✓	✓	✓	✓	✓
	Offset	✓	✓	✓	✓	✓	✓	✓	✓
Miscellaneous	CAD Design	✓	✓	-	-	✓	-	✓	✓
	Cloud Based	-	-	✓	-	-	✓	-	-

Table 1 illustrates that access to customized lattice structures is consistent, as each software has successfully implemented this feature. This emphasizes the significance of customization for lattice design, as it enables the definition of a unique unit cell, thus enhancing product customizability. Moreover, each lattice design software package also includes TPMS lattices and strut-based lattices, which are widely utilized lattice types, indicating that their availability is a crucial feature. However, not all software platforms provide access to planar lattice and stochastic lattice options, suggesting these may be more advanced lattice types or are not as useful to a wide audience.

Table 1 also highlights the primary tools available for lattice component design. Control over the lattice's position and size appears to be essential during the development process illustrated that many lattice design software packages provide tools for grading, offsetting, and conforming. Following lattice application, users may desire the ability to reshape or modify portions of the lattice across various unit cells, whether for aesthetic or functional reasons. Lastly, it is notable that only two of the software applications are cloud-based. This trend likely mirrors that of CAD software more broadly, which is seeing the slow emergence of cloud platforms, bringing a set of new collaborative features and potential workflows which lattice designers could also adopt [27]. The profitability of the cloud approach is a good opportunity for organizations venturing into new web-based services and lacking server capacity [28].

Importantly, Table 1 provides detailed insights into what constitutes a standard lattice software. Since most lattice software options do not offer integrated part design (as you would have in a full CAD package), it is reasonable to assume that this does not significantly impact the user experience, as it may not be the primary focus of lattice design software. While some software packages support the full design of the component, other packages such as Carbon and Ultrasim3D allow for the generation of basic geometric shapes; others require the component to be designed on a separate CAD platform and then imported to the lattice software. This limitation is not likely to be detrimental, considering that CAD software has been widely used for several decades. In contrast, lattice design software is relatively newer, and it can be expected that users who require such software already possess CAD software. Therefore, the inability to create components directly within lattice design software does not greatly influence its overall value.

While the main features are generally similar across most software, the implementation and information processing methods during component latticing vary significantly. This is explored in greater detail in the next section, which examines workflows in each software package.

4.2 Comparison of Design Workflows

In addition to comparing the attributes and unique characteristics of each software, an examination of the entire design process can provide valuable insights into software functionality. Studying these workflows and understanding the information flow can offer relevant perspectives.

Firstly, the flow of information in Metafold 3D, Carbon, Materialise 3-matic, Fusion 360, Siemens NX, and Altair Inspire can be summarized in a few distinctive steps, illustrated in Figure 11. We refer to this as the *Direct Latticing Workflow*. The user selects the component to which the lattice has to be applied, chooses parameters for the lattice, and finally generates it. This particularity makes the six software packages straightforward to use.

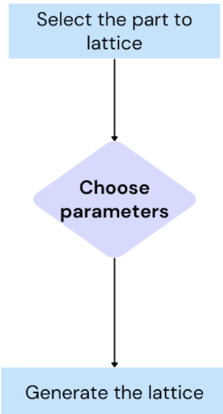

Figure 11: Direct Latticing Workflow

nTop embraces a slightly different workflow (see Figure 12). This software package is constructed based on a modular framework that integrates various tools. As a result, the workflow can vary significantly depending on the user's preferences. However, when it comes to the specific task of latticing a single component, the workflow is similar to the Direct Latticing Workflow, with the primary difference being that the lattice is constructed separately and then intersected with the part. Therefore, we refer to it as the *Lattice Intersection Workflow.*

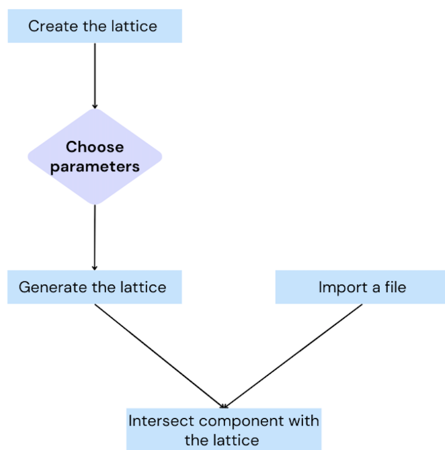

Figure 12: Lattice Intersection Workflow

Finally, the workflow for Ultrasim3D (shown in Figure 13) follows a slightly more complicated approach. Users have to make an initial choice between pre-engineered lattices or entering the lattice playground. Once this decision is made, the latticing process proceeds smoothly, with users needing to make a few decisions such as determining lattice parameters before finalizing the component. We refer to this as the *Advanced Latticing Workflow.*

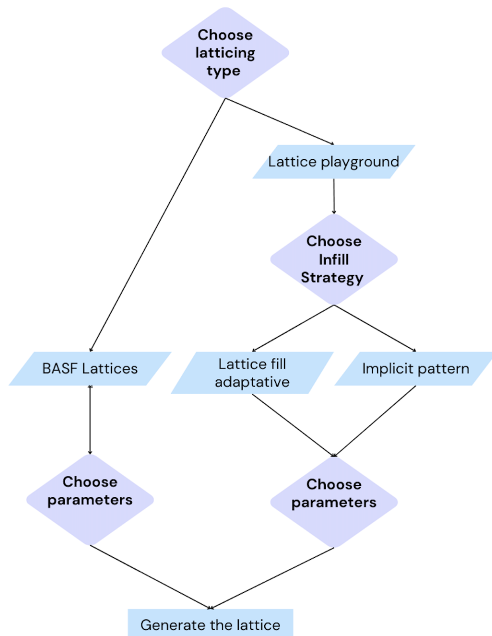

Figure 13: Advanced Latticing Workflow

4.3 Iterative Improvement of Lattices

The use of lattice structures is broad, extending across engineering fields that demand accuracy and rigor. For example, consider the precision required in aerospace applications or such fields, where even a small component with a lattice structure must meet stringent standards. For that reason, this section describes the unique features implemented by various software packages to support optimized outcomes for their users' projects. The ability of a software package to assist the users in the iterative improvement of a lattice design can be an attractive feature, particularly for users with low-to-moderate experience. These approaches are summarized in Table 2 and discussed in greater detail throughout the remainder of this section.

Metafold 3D offers a lattice selection assistance tool to guide users in choosing the most suitable lattice for their product. Initially, the tool prompts users to specify the key properties that are important for their product. Based on these inputs, the choices are narrowed down, and lattices that best match the specified criteria are recommended. Additionally, Metafold 3D provides a static analysis feature that allows users to mechanically test their components under compression, providing valuable insights into the behavior of the product under different conditions.

Carbon Engine provides a lattice library that contains precise information about various lattices they offer, including details such as density, strength, and other behavioral insights. Many lattice behaviors are already documented in their library, which enhances the prediction of the final lattice properties. Additionally, the software employs computational methods to generate lattice designs, enabling it to closely match the desired properties expected by the user for their product. This design generation feature helps save time by automatically providing the optimal properties one could expect from the lattice.

Siemens NX and Fusion 360 offer comprehensive physical simulations that enable users to evaluate the performance of lattices across various applications. These simulations provide a valuable opportunity to assess how the lattice structures behave under different conditions, such as mechanical stress, thermal changes, or fluid dynamics. This ensures that the lattice design aligns with the intended expectations and meets the desired performance standards.

Materialise 3-matic includes simulation and analysis tools for predicting the behavior of 3D printed parts under various loading conditions. Users can perform stress analysis, deformation analysis, and other simulations to optimize part design and ensure structural integrity. Similarly, the software offers the possibility to smoothly export files to Computational Fluid Dynamics or Finite Element Analysis software, enabling the study of the component's characteristics on other software platforms. Furthermore, one can create a Python script to automate processes and files, enhancing workflow efficiency. This tool is designed to handle much of the legwork for the user by automating repetitive tasks, helping to avoid human error.

Ultrasim3D provides a pre-engineered library that grants access to pre-tested lattices with detailed characteristics. Additionally, the software can assist users in selecting a lattice that aligns with their intended application. Upon selecting seating, footwear, or protection, users are guided to a curated lattice selection tailored to their specific requirements. While the use of a test pad is common with this software, it also offers a comprehensive library. Lastly, powered by BASF Hyperganic, the software ensures optimal lattice topology generation. The onboarding process for this software is quick, taking only a few minutes.

Table 2: Summary of iterative improvement features

Software Package	Feature(s)
Altair Inspire	● Physical Simulations ● Optimize lattice mapping
Autodesk Fusion 360	● Physical simulations
Carbon Engine	● Lattice choice assistance ● Optimize lattice mapping
Hyperganic Ultrasim3D	● Lattice choice assistance ● Optimize lattice mapping
Materialise 3-matic	● Physical simulations ● Automated workflow
Metafold 3D	● Lattice choice assistance ● Static Analysis
nTop	● Topology optimization and field-driven design ● Physical simulations
Siemens NX	● Physical Simulations

nTop offers various features that assist the user in optimizing their lattice topology. Starting from a pattern or an image, a lattice can be arranged to meet expectations specific to the product. For instance, the field-driven design enables easy lattice formation for a shoe sole, which necessitates a different lattice topology where the foot rests. Additionally, by providing details about the component, the software can redefine a new topology that optimizes the structures and their properties. Furthermore, nTop provides physical testing, such as static analysis, to ensure the reliability and functionality of the lattice structures.

Altair Inspire offers various features aimed at ensuring the optimal properties of a lattice structure. Firstly, it enables users to conduct physical simulations, including linear static and normal modes analysis, on their models. Moreover, the software provides optimization capabilities for the lattice design. Users can utilize preset options such as minimizing mass or maximizing stiffness, as well as defining parameters like percent reduction in mass. By specifying these optimization criteria, the software adjusts the lattice design accordingly to meet the user's requirements and achieve the desired structural properties.

An analysis of Table 2 illustrates that most of the characteristics enhancing the user's experience fall into three main families. The first one offers lattice choice assistance, sometimes along with an engineered lattice library. Secondly, some software implement physical simulations (mostly using Finite Element Analysis) to gain insights into the behavior of the component under certain inputs. Lastly, some software implement their own topology optimization tool, allowing for an ideal lattice configuration.

4.4 Additional Unique Features

Across the lattice design software packages examined in this work, there exists many different unique features that have been implemented in order to excite the user's experience or to encourage the choice of a certain software over others. In this part of the paper, some interesting aspects of each software will be discussed. These aspects include traits that are distinctive and that make the experience of the particular software exciting.

While each software has its own distinctive features, the objective of this section is to spotlight aspects that may enhance user enthusiasm towards utilizing a specific software. By identifying and elaborating on these features, we aim to showcase why users may find them particularly interesting.

Multi Lattice refers to the ease of latticing a component with many different lattices. This can be applied on products where a certain lattice is needed on a specific region and another is required somewhere else. Apart from Mutli Lattice, none of these features share anything in common, yet they are essential in enhancing the value of each software and facilitating comparison.

While some may perceive these features as simple add-ons, others might consider them indispensable. In other words, the way those features are perceived can vary from a user to another. The main factors are the user's experience in CAD software as well as the familiarity with additive manufacturing. For example, novice users seeking lattice software may find Ultrasim3D's assistance particularly valuable, whereas experienced engineers focused on precise lattice attributes such as area and volume would prioritize software providing comprehensive lattice information over assistance tools. Furthermore, the field of application of the user's lattice will also affect how exciting the features above are. In fact, extreme precision on the properties of a lattice might not be crucial for all applications.

These unique features cater to a diverse range of user needs and preferences, thereby enriching the software capability and offering new solutions for various applications.

Table 3: Summary of Unique features

Software Package	Feature(s)
Altair Inspire	● Multi Lattice
nTop	● Multi Lattice
Metafold 3D	● Provides the exact area and volume of the component
Siemens NX	● Multi Lattice
Carbon Engine	● Access to specific data of the lattice. ● Multi Lattice. ● Preview expected performances
Hyperganic Ultrasim 3D	● Support during the product development by engineers ● Pre engineered library ● Multi Lattice
Materialise 3-matic	● Allows to perform structural design operations on STL files ● Mutli Lattice

5. Conclusion

This paper aimed to present the current status of lattice design software packages as well to perform an accurate comparison of them. This paper has revealed similarities and emerging patterns across different platforms while also highlighting how these software packages have responded to the demanding precision requirements of lattice structures by implementing distinctive features to enhance user experience and differentiate themselves in the market.

Many of the lattice design software packages that were reviewed offer comparable types of lattices, which indicates that these are baseline features which minimally differentiate these product offerings. However, it was also observed that the precise needs of specific industries might have influenced the development of these software packages, resulting in more unique features.

Although this paper offers a rigorous comparison based on largely objective attributes, the evaluation of software can be limited by the subjectivity of the user experience. While various characteristics of software were objectively compared, the overall impression often depends on individual user experience and expectations. Future work should seek to build on the current comparison by directly assessing user experience in these software packages.

Acknowledgements

This material is based upon work supported by the Struminger Junior Faculty Fellowship. Any opinions, findings, and conclusions or recommendations expressed in this work are those of the authors and do not necessarily reflect the views of the sponsors.

References

[1] Ameta, G., and Witherell, P., 2019, "Representation of Graded Materials and Structures to Support Tolerance Specification for Additive Manufacturing Application," J. Comput. Inf. Sci. Eng., **19**(021008).
[2] Khalid, M., and Peng, Q., 2021, "Investigation of Printing Parameters of Additive Manufacturing Process for Sustainability Using Design of Experiments," J. Mech. Des., **143**(032001).
[3] Seharing, A., Azman, A. H., and Abdullah, S., 2020, "A Review on Integration of Lightweight Gradient Lattice Structures in Additive Manufacturing Parts," Adv. Mech. Eng., **12**(6), p. 168781402091695.
[4] Hambleton, D., Ross, E., and Cappadocia, C., "Beyond the Model: Toward a Unified Framework for Geometry Creation, Visualization, Interaction and Iteration."
[5] Ma, S., Tang, Q., Liu, Y., and Feng, Q., 2021, "Prediction of Mechanical Properties of Three-Dimensional Printed Lattice Structures Through Machine Learning," J. Comput. Inf. Sci. Eng., **22**(031008).
[6] Lumpe, T. S., and Shea, K., 2023, "Computational Design of Multi-State Lattice Structures With Finite Mechanisms for Shape Morphing," J. Mech. Des., **145**(071701).
[7] Ross, E., and Hambleton, D., "Using Graph Neural Networks to Approximate Me- Chanical Response on 3D Lattice Structures."
[8] Nguyen, J., Park, S., and Rosen, D., 2013, "Heuristic Optimization Method for Cellular Structure Design of Light Weight Components," Int. J. Precis. Eng. Manuf., **14**(6), pp. 1071–1078.
[9] Nguyen, J., Park, S.-I., Rosen, D. W., Folgar, L., and Williams, J., "Conformal Lattice Structure Design and Fabrication."
[10] Pan, C., Han, Y., and Lu, J., 2020, "Design and Optimization of Lattice Structures: A Review," Appl. Sci., **10**(18), p. 6374.
[11] Chi, Z.-P., Wang, Q.-H., Li, J.-R., and Xie, H.-L., 2023, "A Conformal Design Approach of TPMS-Based Porous Microchannels With Freeform Boundaries," J. Mech. Des., **145**(102001).
[12] Delissen, A., Radaelli, G., Shaw, L. A., Hopkins, J. B., and Herder, J. L., 2018, "Design of an Isotropic Metamaterial With Constant Stiffness and Zero Poisson's Ratio Over Large Deformations," J. Mech. Des., **140**(111405).
[13] Leuenberger, A., Birner, E., Lumpe, T. S., and Stanković, T., 2024, "Computational Design of 2D Lattice Structures Based on Crystallographic Symmetries," J. Mech. Des., **146**(071703).
[14] Stanković, T., and Shea, K., 2020, "Investigation of a Voronoi Diagram Representation for the Computational Design of Additively Manufactured Discrete Lattice Structures," J. Mech. Des., **142**(111704).
[15] Baldwin, M., Meisel, N., and McComb, C., 2022, "A Data-Driven Approach for Multi-Lattice Transitions," Solid Free. Fabr. 2022 Proc. 33rd Annu. Int. Solid Free. Fabr. Symp.

[16] Baldwin, M., Meisel, N., and McComb, C., "Smoothing the Rough Edges: Evaluating Automatically Generated Multi-Lattice Transitions," Solid Free. Fabr. 2022 Proc. 33rd Annu. Int. Solid Free. Fabr. Symp.
[17] Dong, G., Tang, Y., and Zhao, Y. F., 2017, "A Survey of Modeling of Lattice Structures Fabricated by Additive Manufacturing," J. Mech. Des., **139**(100906).
[18] Corney, J., Hayes, C., Sundararajan, V., and Wright, P., 2005, "The CAD/CAM Interface: A 25-Year Retrospective," J. Comput. Inf. Sci. Eng., **5**(3), pp. 188–197.
[19] Qin, Y., Lu, W., Qi, Q., Liu, X., Zhong, Y., Scott, P. J., and Jiang, X., 2016, "Status, Comparison, and Issues of Computer-Aided Design Model Data Exchange Methods Based on Standardized Neutral Files and Web Ontology Language File," J. Comput. Inf. Sci. Eng., **17**(010801).
[20] Cheng, K., Davis, M. K., Zhang, X., Zhou, S., and Olechowski, A., 2023, "In the Age of Collaboration, the Computer-Aided Design Ecosystem Is Behind: An Interview Study of Distributed CAD Practice," Proc. ACM Hum.-Comput. Interact., **7**(CSCW1), pp. 1–29.
[21] Deng, Y., Mueller, M., Rogers, C., and Olechowski, A., 2022, "The Multi-User Computer-Aided Design Collaborative Learning Framework," Adv. Eng. Inform., **51**, p. 101446.
[22] Tang, T. L. E., Liu, Y., Lu, D., Arisoy, E. B., and Musuvathy, S., 2017, "Lattice Structure Design Advisor for Additive Manufacturing Using Gaussian Process," *IDETC-CIE2017*, Volume 1: 37th Computers and Information in Engineering Conference.
[23] Kang, S., Deng, X., and Jin, R., 2021, "A Cost-Efficient Data-Driven Approach to Design Space Exploration for Personalized Geometric Design in Additive Manufacturing," J. Comput. Inf. Sci. Eng., **21**(061008).
[24] Leung, Y.-S., Kwok, T.-H., Li, X., Yang, Y., Wang, C. C. L., and Chen, Y., 2019, "Challenges and Status on Design and Computation for Emerging Additive Manufacturing Technologies," J. Comput. Inf. Sci. Eng., **19**(2), p. 021013.
[25] Saunders, R., Moser, A., and Matic, P., 2019, "A Computationally Efficient Computer-Aided Design Strategy for Iterative Combat Helmet Design and Analysis," J. Eng. Sci. Med. Diagn. Ther., **2**(021003).
[26] Thilmany, J., 1999, "Mechanical Engineering. Oct 1999, 121(10)."
[27] Phadnis, V., Arshad, H., Wallace, D., and Olechowski, A., 2021, "Are Two Heads Better Than One for Computer-Aided Design?," J. Mech. Des., **143**(7), p. 071401.
[28] Fisher, C., 2018, "Cloud versus On-Premise Computing," Am. J. Ind. Bus. Manag., **08**(09), pp. 1991–2006.