Pamukkale Univ Muh Bilim Derg, 30(2), 145-154, 2024

Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi

Pamukkale University Journal of Engineering Sciences

Adaptive topology optimization for additive manufacturing in aerospace applications

Havacılık uygulamalarında eklemeli imalat için uyarlanabilir topoloji optimizasyonu

Mevlüt Yunus KAYACAN[1], *Mamoun ALSHIHABI*[1*]

[1]Department of Mechanical Engineering, Faculty of Technology, Isparta University of Applied Sciences, Isparta, Turkey.
mevlutkayacan@isparta.edu.tr, mamounkhalshihabi@gmail.com

Received/Geliş Tarihi: 22.02.2023 Revision/Düzeltme Tarihi: 17.05.2023 doi: 10.5505/pajes.2023.52578
Accepted/Kabul Tarihi: 26.05.2023 Research Article/Araştırma Makalesi

Abstract

Topology optimization has become a valuable tool in the aerospace industry, enabling engineers to develop aircraft components with improved performance characteristics while reducing their weight. The technique has also allowed for the design of complex structures that were previously unattainable using traditional manufacturing methods. In this study, a comprehensive topology optimization of the steering pump housing for an aircraft's nose landing gear was performed using the nTopology software. The primary objective of this optimization was to reduce the weight of the steering pump housing while preserving its mechanical properties, which are essential for safe and reliable operation of the nose landing gear system. The study demonstrates the potential for topology optimization to be an effective tool for reducing the weight of aircraft components while preserving their mechanical properties. This approach can be applied to other aircraft components with similar design challenges, and could potentially lead to significant weight savings in the overall design of the aircraft.

Keywords: Topology, Optimization, Voronoi, Gyroid, Additive manufacturing.

Öz

Topoloji optimizasyonu, havacılık endüstrisinde önemli bir yöntem ve mühendislerin, ağırlıklarını azaltırken yüksek performanslı uçak bileşenleri geliştirmelerini sağlamıştır. Ayrıca, daha önce geleneksel imalat yöntemleri kullanılarak üretilmesi mümkün olamayacak karmaşık yapıların tasarımına da olanak sağlamıştır. Bu çalışmada, nTopology yazılımı kullanılarak bir uçağın iniş takımları için direksiyon pompası muhafazasının kapsamlı topoloji optimizasyonu gerçekleştirilmiştir. Bu optimizasyonun birincil amacı, iniş takımı sisteminin emniyetli ve güvenilir çalışması için gerekli olan mekanik özelliklerini korurken direksiyon pompası mahfazasının ağırlığını azaltmaktır. Çalışma, topoloji optimizasyonunun, mekanik özelliklerini korurken uçak bileşenlerinin ağırlığını azaltmak için etkili bir araç olduğunu göstermektedir. Bu yaklaşım, benzer tasarım zorluklarına sahip uçak bileşenlerine uygulanarak, potansiyel olarak uçağın genel tasarımında önemli ağırlık tasarrufları sağlayabilecektir.

Anahtar kelimeler: Topoloji, Optimizasyon, Voronoi, Gyroid, Eklemeli imalat.

1 Introduction

As aerospace technology continues to advance, there is an increasing demand for lightweight and high-performance structures that can withstand the rigors of flight. Topology optimization, a powerful computational design tool, has emerged as a promising approach to address this challenge. By systematically exploring the design space and identifying optimal material layouts, topology optimization enables engineers to create complex and efficient structures that are difficult, if not impossible, to achieve using traditional design methods. Topology optimization is a crucial tool for weight reduction in engineering design. By iteratively exploring different material distributions within a given design space, topology optimization can identify the most efficient material layout for a given load-bearing structure. This can lead to significant weight savings while still ensuring that the design meets the necessary performance requirements. Weight reduction is a critical factor in many engineering applications, especially in the aerospace and automotive industries. The aviation industry is constantly seeking ways to reduce fuel consumption and operating costs, and one way to do this is by reducing the weight of parts in an aircraft. Lighter parts can lead to a variety of benefits, including reduced fuel consumption, improved performance and maneuverability, increased reliability, and reduced environmental impact [1]-[3]. One way to achieve weight reduction is through the use of topology optimization, which involves finding the optimal design of a component that meets certain mechanical and structural requirements while minimizing its weight [4],[5]. The part we are working on in this study is the steering pump housing, which is a part of the nose landing gear system that is an essential component of an aircraft's landing gear system, responsible for supporting the weight of the aircraft during takeoff and landing, and providing steering control on the ground. The nose landing gear system typically comprises several components, including the nose gear strut, the steering mechanism, and the wheel and tire assembly. The weight of the nose landing gear system is a critical consideration in aircraft design, as it directly affects the overall weight and balance of the aircraft. According to industry estimates, the weight of the nose landing gear system typically ranges from 318-680 kilograms (in commercial airliners, which accounts for 2-3% of the total weight of a typical commercial airliner, with larger aircraft having a higher percentage due to the increased weight and size of the components. The steering pump housing is a

*Corresponding author/Yazışılan Yazar

critical component of an aircraft's nose landing gear system, responsible for directing the movement of the landing gear. In order to improve the overall efficiency and performance of the aircraft, it is important to optimize the weight and mechanical properties of this part. One way to achieve this is through the use of topology optimization by using computational algorithms to identify the optimal geometry for a given set of design constraints [4],[5]. In this study, we used nTopology, a software platform specialized in additive manufacturing, to conduct a manual topology optimization on the steering pump housing. The use of nTopology in additive manufacturing has become increasingly popular in recent years due to its ability to optimize the design of parts for a variety of applications. By using topology optimization techniques, nTopology can help designers to create parts that are lighter and stronger, while still meeting the required mechanical properties and performance standards [5],[6]. The use of topology optimization can greatly benefit the aviation industry. By reducing the weight of parts in an aircraft not only fuel consumption and operating costs are affected but also lighter parts can lead to reduced stress on other parts of the aircraft, increasing the overall lifespan and reliability of the aircraft [7]. Additionally, lighter aircraft will emit less carbon dioxide and other pollutants, which can greatly benefit the environment [8],[9]. In addition to weight reduction, nTopology can also be used to optimize the structure of parts to improve their performance under different loads and conditions. This can be particularly useful in the design of parts that are subjected to high levels of stress or fatigue, as it allows designers to create structures that are more resistant to failure [10],[11]. This improved performance under loads and conditions can lead to increased safety and reliability of the aircraft [11]. The use of nTopology in additive manufacturing has the potential to revolutionize the way that parts are designed and manufactured, allowing for the creation of lighter, stronger, and more efficient components [12]-[14]. This method can be applied to a variety of parts in an aircraft, leading to the optimization of weight and mechanical properties of the whole aircraft. This research on the steering pump housing serves as a case study, and further studies on other components can lead to greater optimization. Weight reduction in aircraft manufacturing is an important factor that needs to be taken into consideration to improve the overall efficiency and performance of the aircraft [15]. This can greatly benefit the aviation industry, leading to reduced operating costs, improved performance, increased reliability, and reduced environmental impact. Gyroid and Voronoi lattices are two types of lightweight and high-performance structures that are commonly used in aerospace engineering to reduce weight and increase structural efficiency. These lattice structures can be optimized using topology optimization to create complex and efficient structures that are difficult to achieve using traditional design methods. Gyroid lattices are structures that are a type of complex, periodic minimal surface that have been widely studied in the field of mathematics and materials science [16]. In recent years, they have gained popularity in the field of additive manufacturing, as a potential way to create lightweight and strong structures [16],[17]. One of the main benefits of using gyroid lattices in additive manufacturing is their ability to provide a high strength-to-weight ratio [18]. This makes them particularly useful for creating components for aerospace, automotive, and other applications where weight reduction is critical. In addition to their strength-to-weight ratio, gyroid lattices also have the ability to dissipate energy and absorb impact. This makes them well suited for use in energy-absorbing structures, such as protective gear or packaging materials [19]. Gyroid lattices have a complex structure with a continuous curvature, which allows for a high degree of mechanical robustness. This makes them suitable for applications where strength and durability are critical, such as in aerospace or automotive industries. Studies have shown that gyroid lattices can achieve high mechanical strength, with a tensile strength of up to 7.5 MPa and a yield strength of up to 2.5 MPa [20],[21]. Additionally, gyroid lattices have a relatively low relative density of about 10%, making them lightweight and ideal for weight-sensitive applications. There are several additive manufacturing techniques that can be used to create gyroid lattice structures, including selective laser sintering (SLS), fused deposition modeling (FDM), and binder jetting (BJ) [22],[23]. The choice of technique will depend on the specific requirements of the application, including the material being used and the desired final properties of the component. Overall, gyroid lattices offer a promising solution for creating lightweight and strong structures in additive manufacturing, with a wide range of potential applications in various industries. In additive manufacturing, a Voronoi lattice is a type of structure that is created by dividing a three-dimensional space into a series of interconnected cells, each of which is defined by a specific set of geometric criteria [24],[25]. The Voronoi lattice is named after the mathematician Georg Voronoi, who developed the mathematical principles behind this type of structure in the 19th century. In the context of additive manufacturing, Voronoi lattices can be used to create complex, lightweight structures with a high degree of structural integrity [24],[25]. Voronoi lattices have a regular, repeating structure that provides greater uniformity in their mechanical properties. Voronoi lattices are known for their high specific strength, which is the ratio of strength to density. Specific strength is an important factor in applications where weight reduction is critical, such as in aerospace or biomedical implants. Studies have shown that Voronoi lattices can achieve a specific strength of up to 400 MPa/mm, which is significantly higher than that of other lattice structures. Voronoi lattices also have a relatively high relative density of about 25%, which means that they offer a good balance between strength and weight [26],[27]. These structures can be created using a variety of different additive manufacturing techniques, including 3D printing, laser sintering, and other processes. One of the key benefits of using a Voronoi lattice in additive manufacturing is that it allows for the creation of structures that are both strong and lightweight. As a result, the structure is able to distribute loads evenly throughout the part, which helps to reduce the overall weight of the part while maintaining its strength and stability. In addition to their use in additive manufacturing, Voronoi lattices have also been used in a variety of other applications, including structural engineering, material science, and even biology. By optimizing the weight and mechanical properties of critical components, such as the steering pump housing, the aviation industry can benefit from reduced fuel consumption, improved performance and maneuverability, and increased reliability. Lighter aircraft parts not only lower fuel consumption, but also reduce stress on other parts, extending the lifespan of the aircraft. The use of topology optimization can also lead to a lighter carbon footprint as it can reduce the carbon footprint of aircraft by up to 5% [28]. The study on the steering pump housing serves as a shining example of the potential of topology optimization and further research on other components can bring even greater advancements to the field. Within the scope of this study, a steering pump housing was analyzed and optimized to get weight savings as well as structural integrity. The gyroid and Voronoi lattices were used to obtain new designs resulting in two unique lattice-infused parts. After the part was infused with the two lattices static analyses were conducted to observe the behaviors of the designs under various loads. When the results came in positive it wasn't surprising as it's well known that these lattice structures are light weight and mechanically preservable.

2 Materials and methods

The steering pump housing was made of 201.0-T7 Aluminum and was manufactured through sand casting. With a tensile yield strength of 345 MPa and a density of 2.8 g/cm³ as shown in Table 1. Our goal was to reduce the weight of the component as much as possible while maintaining its mechanical properties. Sand casting is a common manufacturing process used to produce complex-shaped parts made of aluminum alloy [29]. Through manual topology optimization, we were able to achieve a significant reduction in the mass of the steering pump housing while ensuring that the Von Mises stress values remained within the required limit of 345 MPa.

Table 1. Physical and mechanical properties of sand casted Aluminum 201.0-T7.

Physical Properties	Metric
Density	2.80 g/cc
Mechanical Properties	Metric
Hardness, Brinell	110 - 140
Hardness, Knoop	157
Hardness, Rockwell A	47
Tensile Strength, Ultimate	>= 414 MPa
Tensile Strength, Yield	>= 345 MPa
Elongation at Break	>= 3.0 %
Tensile Modulus	71.0 GPa
Poisson's Ratio	0.33
Fatigue Strength	98.0 MPa

Aluminum 201.0-T7 alloy is commonly used in sand casting due to its good mechanical properties and low cost. Sand casting is a simple and cost-effective method for producing parts with complex shapes and high tolerances [29],[30]. It is widely used in the aerospace, automotive, and construction industries due to its versatility and low production cost [31]. However, sand casting has some limitations, such as high material waste and a relatively long production time. Despite these limitations, sand casting remains a popular choice for producing parts. The nose landing gear system (as shown in Figure 1.) consists of multiple components, such as the nose gear strut, steering mechanism, and wheel and tire assembly.

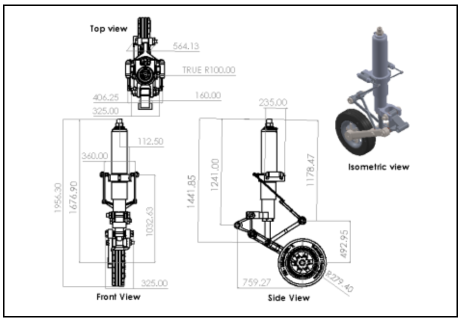

Figure 1. Nose Landing Gear System and it's measurements in millimeters.

Prior to optimization, the steering pump housing underwent a thorough analysis process where it was measured and assigned the appropriate material properties to ensure it's accurate dimensions as shown in Figure 2. All the collected measurements and material data were saved to the CAD file before importing it into nTopology.

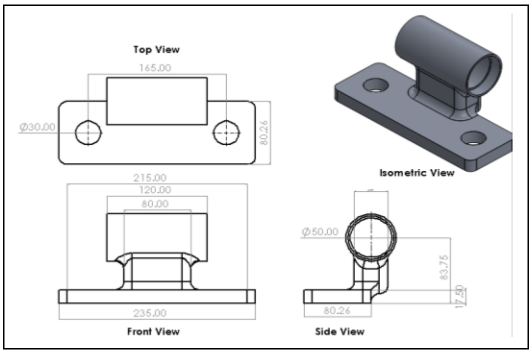

Figure 2. Steering Pump Housing and it's measurements in millimeters.

In this project, we utilized the software platform nTopology to optimize the design of a steering pump housing for a specific application. The process began by importing the existing part into nTopology as a STEP file, which is a common 3D model file format that allows for the transfer of complex 3D geometry between different CAD software progr [32]. Once the part was imported, it was converted into an implicit body, which is a 3D geometry represented by a distance field. Implicit bodies are the default working geometry in nTopology, and they offer a number of benefits when it comes to design optimization. For example, implicit bodies can be more flexible and easier to manipulate than traditional CAD geometry, and they can be used to generate a wide range of design variations quickly and easily.

In this study multiple mathematical equations that represent various concepts in the field of structural mechanics are used, including finite element analysis and design optimization. The equations cover topics such as the stiffness matrix of a finite element model, the objective function used in topology optimization, the element strain energy, shape sensitivity analysis, element stress calculations, and the displacement interpolation function used in finite element analysis. These equations provide a fundamental understanding of the underlying mechanics of these methods and are important tools in the design and analysis of structures.

$$K = B^T * D * B * \det(J) \tag{1}$$

The finite element stiffness matrix equation is a fundamental equation in the field of finite element analysis, which is used to approximate the behavior of complex structures and systems. K is the stiffness matrix of the system, B is the strain-displacement matrix, D is the material property matrix, det(J) is the determinant of the Jacobian matrix.

$$\min\{x\}\, subject\ to\ c(x) = 0\ and\ ceq(x) = 0.\, lb \leq x \leq ub \tag{2}$$

The topology optimization problem statement is a mathematical formulation that is commonly used in engineering design to find the optimal distribution of material within a given design domain. The problem is formulated as an optimization problem and is typically solved using numerical methods. {x} is the design variable vector, c(x) is a set of inequality constraints that must be satisfied for the design to be feasible., ceq(x) is a set of equality constraints that must also be satisfied for the design to be feasible., and lb and ub are the lower and upper bounds on the design variables.

$$J = 0.5 * u^T * K * u \tag{3}$$

The compliance minimization objective function is a common objective function used in structural optimization problems. The objective of this function is to minimize the structural deformation, or compliance, subject to a set of constraints. The compliance of a structure is a measure of the displacement of the structure under a given load. J is the objective function, u is the displacement vector and K is the stiffness matrix.

$$We = \frac{1}{2} * u^T * D * e * u * \det(J) \tag{4}$$

The element strain energy equation is a fundamental equation in finite element analysis and is used to calculate the total strain energy of an individual finite element. This equation is based on the principle of virtual work and is used to calculate the internal energy stored in the finite element due to the deformation under an external load. W_e is the strain energy of the finite element. u is the displacement vector of the nodes of the finite element. D is the constitutive matrix that relates the stress and strain in the finite element. e is the strain vector, det(J) is the determinant of the Jacobian matrix.

$$\frac{dJ}{dx} = -u^T * K \tag{5}$$

Shape sensitivity analysis is an important tool used in structural optimization problems to calculate the sensitivity of the objective function with respect to changes in the shape of the structure. dJ/dx is the shape derivative of the objective function, u is the displacement vector of the nodes of the structure and K is the stiffness matrix.

$$s = D * e \tag{6}$$

The element stress tensor equation is a fundamental equation in finite element analysis and is used to calculate the stress in an individual finite element. This equation is based on the constitutive relationship between the stress and the strain in the material, which is represented by the constitutive matrix D. s is the stress tensor, D is the constitutive matrix and e is the strain tensor.

$$u = N * u_e \tag{7}$$

The finite element displacement interpolation function is used in finite element analysis to approximate the displacement of nodes within an element. It is a linear combination of the nodal displacements and shape functions defined over the element. u is the displacement vector for the entire element, N is the matrix of shape functions for the element and u_e is the vector of nodal displacements.

To set the boundary conditions for the optimization process, it was necessary to separate the CAD faces into different sets. The first set contained the faces that would experience forces, which were located inside the pipe of the steering pump housing. These faces were selected because they would be subjected to the most stress and deformation during operation, and they needed to be taken into account in order to ensure the structural integrity of the part. The second set contained the fixed faces, which were the two holes of the steering pump housing**.** These faces were designated as fixed because they would not be subjected to any movement or deformation during operation, and they needed to be taken into account in order to accurately model the behavior of the part under load. Finally, the third set contained the whole CAD geometry of the part. This set was used to ensure that all of the relevant geometry was taken into account during the optimization process, and to ensure that the resulting design met all of the necessary performance and safety requirements. One important consideration during the optimization process was the mass of the steering pump housing. We were unable to optimize or reduce the mass of the pipe of the housing, because it was connected to the lever Y handle of the nose landing gear and it needed to remain unchanged for safety reasons. As a result, we seperated the upper part from the lower part as shown in Figure 3. We focused our efforts on the lower part of the housing, which could be optimized and mass-reduced without compromising the structural integrity of the part. To achieve this, we used a combination of topology optimization and mass reduction techniques to generate a range of design alternatives that met the required performance and safety standards. Once we had identified the most promising design, we used a Boolean union to connect it to the upper part of the housing, which was the pipe. This allowed us to create a final design that was both structurally sound and as lightweight as possible, while still meeting all of the necessary performance and safety requirements.

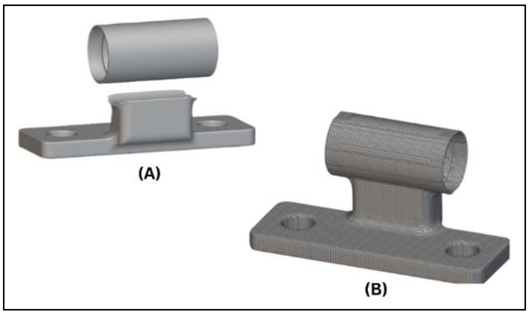

Figure 3. Figure (A) is the part seperated, Figure (B) is the mesh of the part.

Before beginning the topology optimization process, it was important to conduct a static analysis of the normal part in order to understand its behavior under load [33],[34]. In nTopology, the static analysis block is a tool that allows users to perform static structural analysis on a design. This means that the tool can calculate the internal forces and deformations that would occur in a structure under a given set of loads and boundary conditions. The static analysis block can be used to validate the structural integrity of a design, identify potential failure points, and optimize the design for strength and stiffness [35]. It can be applied to a wide range of structural systems, including beams, trusses, frames, and shells. To use the static analysis block, users first need to define the loads and boundary conditions that will be applied to the structure. They can then specify the material properties of the structure and any additional constraints or assumptions that are needed for the analysis. Once these inputs are defined, the static analysis block will solve for the internal forces and deformations in the structure, and provide graphical and numerical results that can be used to understand the behavior of the structure under the given conditions. Conducting a static analysis of the normal part would allow us to compare the results of the optimization process to the baseline performance of the normal part, and ensure that the optimized design was an improvement. To conduct the static analysis, we first needed to create a finite element (FE) model of the normal part. This involved several steps, including creating a mesh from the implicit body of the part, generating a volume mesh with a tolerance and edge length of 5 mm (as shown in Figure 3.), and creating an FE volume mesh with a linear geometric order. We then associated the meshes with a selected CAD body to create an FE component, which represented our FE model of the normal part. In addition to the FE model, we also needed to define the material properties and boundary conditions for the analysis. For the material, we selected AL 201.0 t7, which was material of the part.

For the boundary conditions, we applied a -24000 N force on the Z axis of the pipe and an 8000 N force on the X axis of the pipe, as these were the locations where the forces would be applied in real life as shown in Figure 4. The values of 24000 N and 8000 N were chosen by observing the part's behaviour under multiple forces that we applied to maximise the stress value without exceeding the tensile yield strength of the material, which was 345 MPa. The yellow arrows in the pipe represent the force vectors and the red dots respresent the displacment restraint that were applied on the two holes of the part as shown in Figure 4.

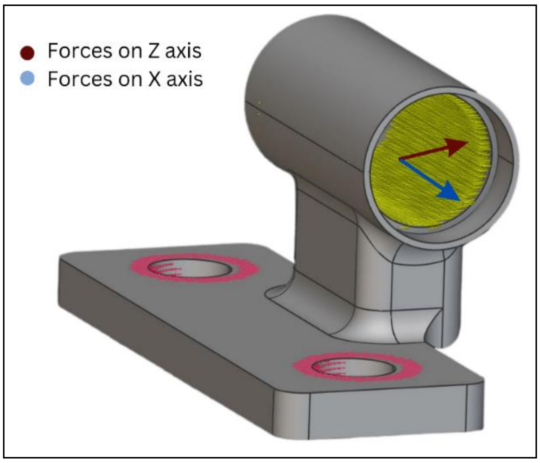

Figure 4. Forces and displacement restraints applied to the part.

Application of a gyroid lattice into the inner volume of the design can be achieved using the Boolean intersect block. By doing so, the inner volume would be transformed into a lightweight structure without compromising its strength. This lattice-infused inner volume creates a part that is structurally sound and lightweight. The intricate, interconnected structure of a gyroid lattice allows it to distribute loads evenly (as shown in Figure 5), resulting in a lightweight yet strong structure.

Utilizing a Voronoi lattice to a 3D model can be a straightforward process compared to other methods This is because the Voronoi lattice consists of a series of interconnected cells, each of which is defined by a specific set of geometric criteria as shown in Figure 6. One of the advantages of using a Voronoi lattice is that a single block can be used to automatically generate the shell and apply the lattice. This approach can save significant time and effort compared to manually creating the shell and lattice separately. The block automatically adjusts the lattice's size and placement according to the selected section's shape and dimensions.

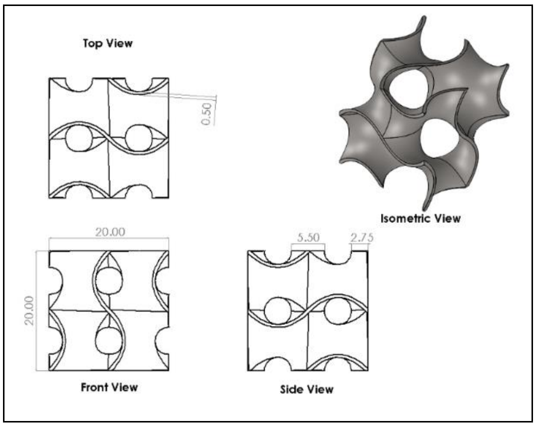

Figure 5. Gyroid unit cell.

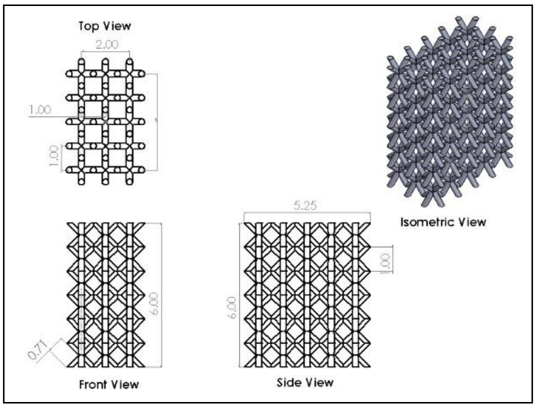

Figure 6. stochastic Voronoi lattice unit cell.

Also stress and strain values were analyzed on 30 different points on the original part, the gyroid infused part and the Voronoi infused part. 15 of those points were taken horizontally along the body of the part and 15 of them were taken vertically as shown in Figure 7.

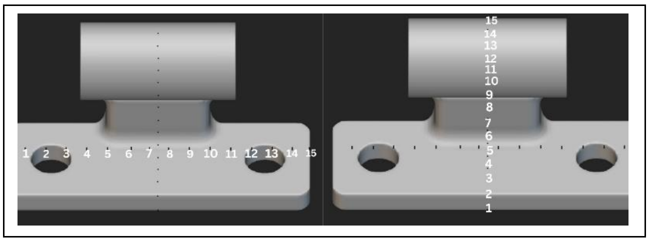

Figure 7. Point number system for analyzing stress and strain values.

3 Results and discussion

Once the FE model, material properties, and boundary conditions were defined, we were ready to begin the static analysis. This involved solving for the Von Mises stress values and strain values of the normal part under the applied loads, and comparing the results to the required performance and safety standards. By understanding the behavior of the normal part under load, we were able to identify areas where the design could be improved, and use this information to guide the optimization process. The results of the static analysis indicate that the structure experienced a range of stresses, with a minimum von Mises stress value of 1.55 MPa a maximum von

Mises stress value of 312.92 MPa and a maximum strain value of 0.0046. The highest stress was observed in the lower section of the part that connects the pipe to the body. The lowest stress was observed on the outer edge of the body. The analysis results are shown in Figure 8. Overall, these results suggest that the structure is subjected to significant stresses, particularly in the lower section of the part that connects the pipe to the body.

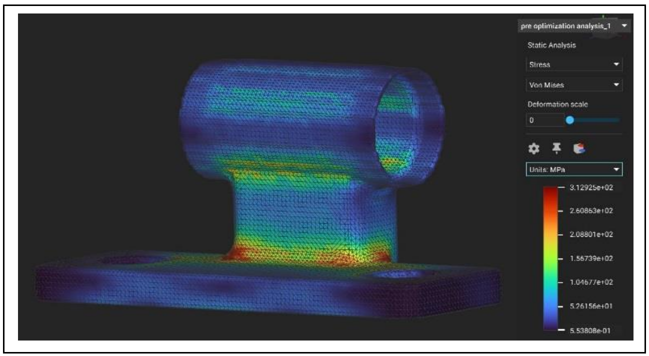

Figure 8. Graphical static analysis result of the pre-optimized part.

In order to optimize the lower body for weight reduction, we first started by creating a shell of the body with a thickness of 3.2 mm. We then subtracted the shelled body from the full body, leaving us with only the inner volume. The inner volume was then infused with a gyroid lattice using the Boolean intersect block. This lattice-infused inner volume was then connected to the hollow shelled body, resulting in a lightweight, yet structurally sound design. The final step was to connect the combined inner volume and shelled body to the upper part, which in this case was the pipe. All these steps are shown in Figure 9. Using this design process, we were able to significantly reduce the weight of the lower body while maintaining its structural integrity. The use of the gyroid lattice allowed us to achieve a lightweight design without sacrificing strength, making it an ideal choice for optimizing the lower body. Overall, this design process proved to be a successful method for reducing weight in the lower body while still meeting the necessary performance requirements. The inner volume we extracted from the body was infused with Gyroid lattice.

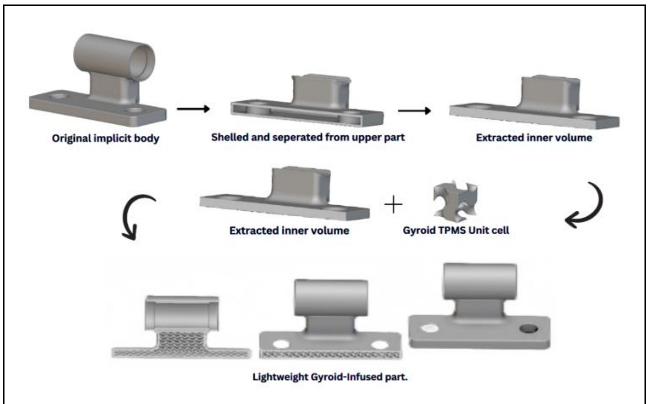

Figure 9. Steps of infusing Gyroid lattice with the part.

After applying the gyroid lattice to the inner volume of the steering pump housing, we performed a new static analysis to ensure that the mechanical properties of the part were preserved. The results of the analysis showed that the maximum Von Mises stress value was 343.85 MPa and the maximum strain was 0.0051, indicating that the mechanical properties of the lightweight part were successfully preserved as shown in Figure 10. In addition to maintaining the mechanical properties of the part, the use of the gyroid lattice also resulted in a significant reduction in weight.

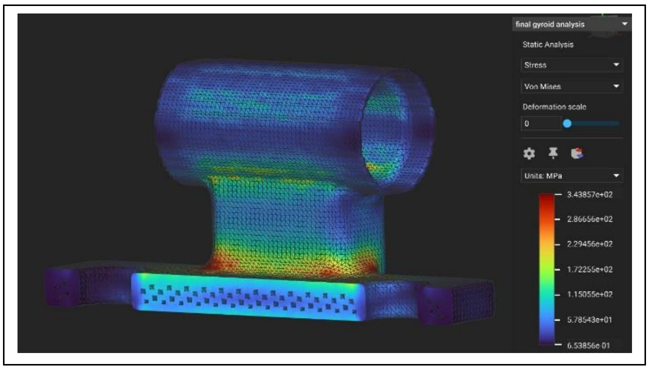

Figure 10. Graphical static analysis result of the Lightweight Gyroid-Infused part.

The new mass of the part was 998.69 gr, representing a 473.26-gram reduction or a 32.15% reduction in weight. This weight reduction is significant and could have a significant impact on the overall performance and efficiency of the system in which the steering pump housing is used. Overall, the use of the gyroid lattice in the design of the steering pump housing was successful in both preserving the mechanical properties of the part and reducing its weight. This demonstrates the potential of using gyroid lattices in additive manufacturing to create lightweight and strong components for a wide range of applications.

Applying a Voronoi lattice to a 3D model can be a simpler process than using other methods. One of the benefits of using a Voronoi lattice is that a single block can be used to automatically generate the shell of the model and apply the lattice. This can save time and effort compared to manually creating the shell and applying the lattice separately. The block will automatically adjust the size and placement of the lattice based on the shape and dimensions of the selected section. After the lattice has been applied, we then connect the Voronoi body to the upper pipe part as shown in Figure 11. This can be done by using Boolean union block.

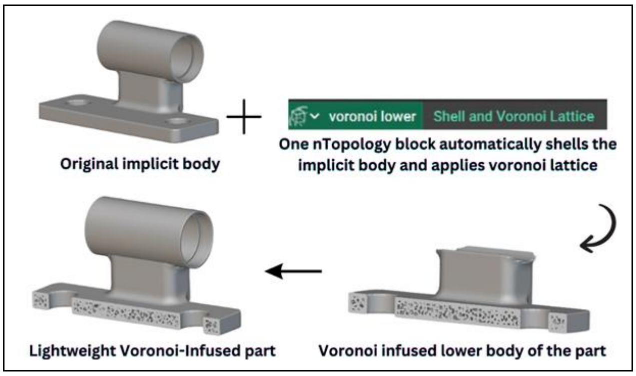

Figure 11. Lightweight Voronoi-Infused part.

After applying the Voronoi pattern to the inner volume of the steering pump housing, we conducted a new static analysis to verify that the mechanical properties of the redesigned part were preserved. The results of the analysis showed that the maximum Von Mises stress value was 344.86 MPa and the maximum strain was 0.00515, indicating that the mechanical properties of the lightweight steering pump housing were successfully preserved as shown in Figure 12. The use of the Voronoi pattern in the design of the steering pump housing not only preserved the mechanical properties of the part, but also resulted in a significant reduction in weight. The new mass of the part was 908.11 gr, representing a 563.84-gram reduction or a 38.30% reduction in weight. This weight reduction is substantial and could have a significant impact on the overall performance and efficiency of the system in which the steering pump housing is used. Overall, the use of the Voronoi pattern in the design of the steering pump housing was a successful method for preserving the mechanical properties of the part while also reducing its weight. This demonstrates the potential of using advanced design techniques, such as the Voronoi pattern, to create lightweight and strong components for a wide range of applications.

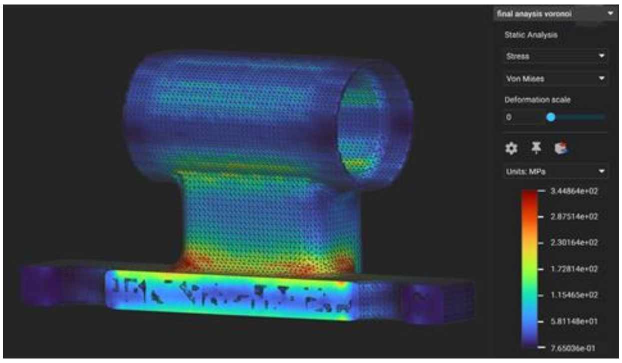

Figure 12. Graphical static analysis result of the Lightweight Voronoi-Infused part.

The main objective of this study was to investigate the potential of topology optimization as a tool for reducing the weight of the steering pump housing for an aircraft's nose landing gear system while preserving its mechanical properties. To achieve this, a finite element model of the steering pump housing was created using the nTopology software and subjected to various loading conditions to simulate the stresses that the part would experience during operation. The optimization algorithm was then used to iteratively adjust the design of the steering pump housing to find the optimal configureuration that minimized weight while maintaining the necessary mechanical properties. The results of the study show that both the Gyroid lattice and the Voronoi lattice were effective methods for optimizing the weight of the steering pump housing while preserving its mechanical properties. It is worth noting that the choice of lattice structure will depend on the specific requirements of the component and the aircraft as a whole. The Gyroid lattice offers a unique combination of isotropic and anisotropic properties, which may be beneficial in certain aerospace applications, while the Voronoi lattice offers more flexibility and potential for greater weight reduction, which may be more suitable in other applications. Additionally, it is important to mention that this study only considered the static load case, further studies are needed to evaluate the behaviour of the optimized design under dynamic loads and also under thermal loads. The utilization of nTopology software in this study highlights its capabilities in providing optimized design solutions for aerospace applications. In our study, we aimed to optimize the weight of a steering pump housing using two different lattice structures: a Gyroid lattice and a Voronoi lattice. We first applied a gyroid lattice to the inner volume of the steering pump housing, using a shell thickness of 3.2 mm and the Boolean intersect block to connect the lattice to the shelled body. After performing a static analysis, we found that the maximum Von Mises stress value was 343.85 MPa, indicating that the mechanical properties of the lightweight steering pump housing were preserved. The new mass of the part was 998.69 gr, representing a weight reduction of 473.26 gr or 32.15% as shown in Table 2. Next, we applied a Voronoi lattice to the steering pump housing using a similar process. The Voronoi lattice was created using a single block that automatically performed the shelling and applied the lattice. We then connected the Voronoi body to the upper pipe part and conducted a static analysis to verify the mechanical properties of the redesigned part. The results of the analysis showed that the maximum Von Mises stress value was 344.86 MPa, indicating that the mechanical properties of the Voronoi lightweight steering pump housing were successfully preserved. The new mass of the part was 908.11 gr, representing a weight reduction of 563.84 gr or 38.30% as shown in Table 2. Weight reduction in the nose landing gear system that is done in this study can be multiplied by two, as there are two steering pump housings in each system. Using the gyroid lattice optimization, an overall weight reduction of 946.52 gr can be achieved, while the voronoi lattice optimization can result in an overall weight reduction of 1127.68 gr. Overall, our results showed that both the Gyroid lattice and the Voronoi lattice were effective methods for optimizing the weight of the steering pump housing while preserving its mechanical properties. The Voronoi lattice resulted in a slightly greater weight reduction, but both lattice structures demonstrated the potential to significantly reduce the weight of the component while maintaining its structural integrity. In conclusion, the topology optimization of the steering pump housing for an aircraft's nose landing gear demonstrated the effectiveness of using nTopology software to reduce the weight of parts while preserving their mechanical properties. The optimized design resulted in a significant weight reduction without exceeding the maximum allowable Von Mises stress values. The application of a Voronoi and Gyroid lattices to the redesigned part maintained the necessary mechanical properties, further highlighting the potential for topology optimization in the design of lightweight components. The ability to optimize the internal structure of parts to reduce weight while maintaining mechanical properties will not only lead to significant cost savings but also enable the production of parts that were previously not feasible with traditional manufacturing methods. Overall, this study showcases the benefits of topology optimization in additive manufacturing and its potential to revolutionize the way parts are designed and produced in the future.

Table 2. Results of gyroid and voronoi lattice structures.

Lattice Type	Initial Mass	Weight Reduced	Percentage of Reduction	Final Mass	Max Von Mises stress	Max Strain
Gyroid	1471.95 gr	473.26 gr	32.15%	998.69 gr	343.85 MPa	0.0051
Voronoi	1471.95 gr	563.84 gr	38.30%	908.11 gr	344.86 MPa	0.00515

A line chart has been made containing three lines one representing horizontal stress of the original part, one representing horizontal stress of the gyroid-infused part and one representing horizontal stress of Voronoi-infused part as shown in Figure 13. Here the Voronoi-infused part showed the highest stress value at point number 5 while the gyroid-infused part also showed a high stress value at point number 10 but lower than the Voronoi-infused part. At points 1 and 15 all the lines showed a relatively low stress.

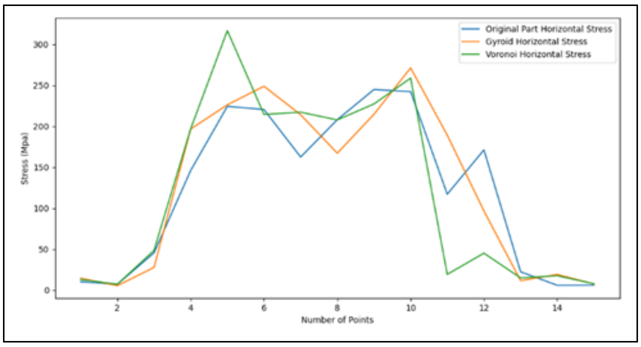

Figure 13. Line chart of the horizontal stress values of the three parts.

This line chart has also been made containing three lines one representing vertical stress of the original part, one representing vertical stress of the gyroid-infused part and one representing vertical stress of Voronoi-infused part as shown in Figure 14. On this set of points the original part and the gyroid-infused part showed the highest stress values at point number 10 with the Voronoi-infused part also showing high stress at point number 11. At point 2 all the lines showed a relatively low stress.

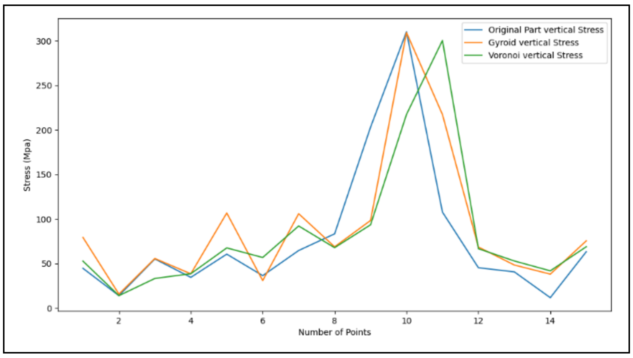

Figure 14. Line chart of the vertical stress values of the three parts.

This chart also contains three lines one representing horizontal strain of the original part, one representing horizontal strain of the gyroid-infused part and one representing horizontal strain of Voronoi-infused part as shown in Figure 15. Here the Voronoi-infused part showed the highest strain value at point number 5 with the original part also showing a high strain value at point number 6 but lower than the Voronoi-infused part. At point 1, 2 and 15 all the lines showed a relatively low strain.

This chart also has three lines one representing vertical strain of the original part, one representing vertical strain of the gyroid-infused part and one representing vertical strain of Voronoi-infused part as shown in Figure 16. On this set of points the Voronoi-infused part showed the highest strain at point number 6 with the second highest being the gyroid-infused part at number 10. At point 1 the gyroid vertical strain line showed the lowest value of strain.

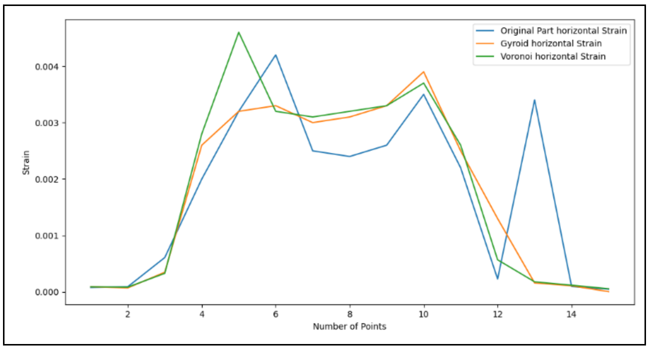

Figure 15. Line chart of the horizontal strain values of the three parts.

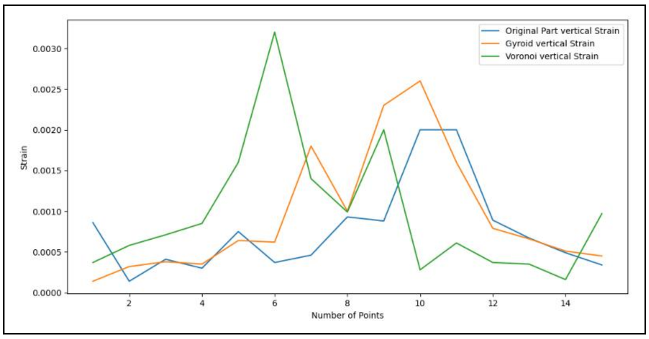

Figure 16. Line chart of the vertical strain values of the three parts.

In one major topology optimization study, a comparable methodology was employed along with a similar analysis. In that study, a reduction in mass of 28.3% was accomplished, accompanied by a corresponding increase of 10 MPa in Von-Mises stress values [36]. And in another major topology optimization study a 20 % weight reduction was achieved successfully [37]. In contrast, this study achieved a superior reduction of 38.3%, despite a marginally higher stress disparity of approximately 32 MPa. This study highlights the potential of topology optimization in additive manufacturing, particularly for the aerospace industry where weight reduction is a critical factor. With the increasing adoption of additive manufacturing in various industries, topology optimization has the potential to play a significant role in the design of lightweight and mechanically sound parts. Moreover, as additive manufacturing technology continues to evolve and improve, topology optimization will likely become even more important in the design of parts for various applications.

4 Conclusions

In this study, the weight of a steering pump housing for an aircraft's nose landing gear was optimized using two lattice structures: a Gyroid lattice and a Voronoi lattice. The Gyroid lattice was applied first, resulting in a weight reduction of 32.15% and a maximum Von Mises stress value of 343.85 MPa. The Voronoi lattice was then applied, resulting in a weight reduction of 38.30% and a maximum Von Mises stress value of 344.86 MPa. Both lattice structures were effective in reducing the weight of the component while maintaining its structural integrity.

Some of the results of the study:

1. The study successfully demonstrated the effectiveness of using nTopology software for topology optimization in the design of lightweight components for aircraft nose landing gear systems,
2. The study applied two different lattice structures, a Gyroid lattice and a Voronoi lattice, to the steering pump housing and found that both methods were effective in optimizing weight while preserving mechanical properties,
3. The Gyroid lattice resulted in a weight reduction of 32.15%, while the Voronoi lattice resulted in a slightly greater weight reduction of 38.30%,
4. The maximum allowable Von Mises stress values were not exceeded in either of the optimized designs, indicating that the mechanical properties of the parts were successfully preserved,
5. The study highlights the potential for topology optimization in additive manufacturing, particularly for the aerospace industry where weight reduction is a critical factor, and suggests that topology optimization will likely become even more important in the design of parts for various applications as additive manufacturing technology continues to evolve and improve.

This study shows that topology optimization with nTopology reduces the weight of parts while maintaining mechanical properties so the findings could be applied to optimize other aircraft components, which reduces fuel consumption and operating costs. Using different lattice structures with topology optimization can be explored for further weight reduction. The investigation of topology optimization's impact on manufacturability and its practical implementation supported by statical and dynamical experimental tests can be further researched. These techniques can also be applied to different parts of an aircraft, providing opportunities for additional research and publications.

5 Author contribution statements

In the scope of this study, Mevlüt Yunus KAYACAN, was the creator of the idea, the design boundary conditions and the literature review; Mamoun ALSHIBABI was the executor of the ideas, the optimizer of design, the creator of the analyses and concluder of results.

6 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person/institution in the article prepared.

7 References

[1] Noronha W, Joshi V, Jeyanthi S. "Design of 3D printed aircraft seat structure using latticing in combination with topology optimization and generative design". *International Conference on Applications in Computational Engineering and Sciences*, Chennai, India, 30-31 October 2020.

[2] Munk DJ, Waddell E, Vaziri R, Gärtner T. "On the benefits of applying topology optimization to structural design of aircraft components". *Structural and Multidisciplinary Optimization*, 60(4), 1245-1266, 2019.

[3] Prathyusha ALR, Raghu Babu G. "A review on additive manufacturing and topology optimization process for weight reduction studies in various industrial applications". *Materials Today: Proceedings*, 62, 109-117, 2022.

[4] Wu J, Sigmund O, Groen JP. "Topology optimization of multi-scale structures: a review". *Structural and Multidisciplinary Optimization*, 63(3), 1455-1480, 2021.

[5] Meng L, Zhang W, Quan D, Shi G, Tang L, Hou Y, Gao T. "From topology optimization design to additive manufacturing: Today's success and tomorrow's roadmap". *Archives of Computational Methods in Engineering*, 27(3), 805-830, 2020.

[6] Tyflopoulos E, Steinert M. "A Comparative study of the application of different commercial software for topology optimization". *Applied Sciences*, 12(2), 1-23, 2022.

[7] Jafferson JM, Sharma H. "Design of 3D printable airless tyres using NTopology". *Materials Today: Proceedings*, 46, 1147-1160, 2021.

[8] Dagkolu A, Gokdag I, Yilmaz O. "Design and additive manufacturing of a fatigue-critical aerospace part using topology optimization and L-PBF process". *Procedia Manufacturing*, 54, 238-243, 2021.

[9] Baumeister S, Leung A, Ryley T. "The emission reduction potentials of first generation electric aircraft (FGEA) in Finland". *Journal of Transport Geography*, 85, 1-8, 2020.

[10] Gray N, McDonagh S, O'Shea R, Smyth B, Murphy JD. "Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors". *Advances in Applied Energy*, 1, 1-24, 2021.

[11] Oh MK, Lee DS, Yoo J. "Stress constrained topology optimization simultaneously considering the uncertainty of load positions". *International Journal for Numerical Methods in Engineering*, 123(2), 339-365, 2022.

[12] Essassi K, Rebiere JL, ElMahi A, Souf MAB, Bouguecha A, Haddar M. "Experimental and analytical investigation of the bending behaviour of 3D-printed bio-based sandwich structures composites with auxetic core under cyclic fatigue tests". *Composites Part A: Applied Science and Manufacturing*, 131, 1-21, 2020.

[13] Miralbes R, Santamaria N, Ranz D, Gómez JA. "Study of the anisotropy of triple periodic minimal surface structures generate by additive manufacturing". *International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing*, Ischia, Italy, 1-3 june 2022.

[14] Sulaymon TA, Petri HT, Rayko T. "Towards a complex geometry manufacturing: A case study on metal 3D printing of topology optimised bicycle parts with lattices". IFAC-PapersOnLine, 55(10), 1515-1520, 2022.

[15] Nirish M, Rajendra R. "Suitability of metal additive manufacturing processes for part topology optimization-A comparative study". *Materials Today: Proceedings*, 27, 1601-1607, 2020.

[16] Moj K, Robak G, Owsiński R, Kurek A, Żak K, Przysiężniuk D. "A new approach for designing cellular structures: design process, manufacturing and structure analysis using a volumetric scanner". *Journal of Mechanical Science and Technology*, 37, 1113-1118, 2023.

[17] Harithsa SN, Kumar SA, Nagesha BK, Nataraj JR. "Computational study on subsonic impact resistance of lattice structures in 3D printed thin Ti6Al4V parts". *Materials Today: Proceedings*, 87(1), 74-79, 2023.

[18] Jihong ZHU, Han ZHOU, Chuang WANG, Lu ZHOU, Shangqin YUAN, Zhang, W. "A review of topology optimization for additive manufacturing: Status and challenges". *Chinese Journal of Aeronautics*, 34(1), 91-110, 2021.

[19] Sathishkumar N, Vivekanandan N, Balamurugan L, Arunkumar N, Ahamed I. "Mechanical properties of triply periodic minimal surface-based lattices made by PolyJet printing". *Materials Today: Proceedings*, 22, 2934-2940, 2020.

[20] Nakanishi K, Labonte D, Cebo T, Veigang-Radulescu VP, Fan Y, Brennan B, Fleck NA. "Mechanical properties of the hollow-wall graphene gyroid lattice". *Acta Materialia*, 201, 254-265, 2020.

[21] Szatkiewicz T, Laskowska D, Bałasz B, Mitura K. "The ınfluence of the structure parameters on the mechanical properties of cylindrically mapped gyroid TPMS fabricated by selective laser melting with 316L stainless steel powder". *Materials*, 15(12), 1-22, 2022.

[22] Yang L, Wu S, Yan C, Chen P, Zhang L, Han C, Shi Y. "Fatigue properties of Ti-6Al-4V Gyroid graded lattice structures fabricated by laser powder bed fusion with lateral loading". *Additive Manufacturing*, 46, 1-18, 2021.

[23] Fu YFJ. "Recent advances and future trends in exploring Pareto-optimal topologies and additive manufacturing-oriented topology optimization". *Mathematical Biosciences and Engineering*, 17(5), 4631-4656, 2020.

[24] Goodwin LA, Schmidt DW, Kuettner L, Patterson BM, Walker E, Edgar A, Schmitt MJ. "Development of stochastic voronoi lattice structures via two-photon polymerization". *Fusion Science and Technology*, 78(1), 66-75, 2022.

[25] Lei HY, Li JR, Xu ZJ, Wang QH. "Parametric design of Voronoi-based lattice porous structures". *Materials & Design*, 191, 1-10, 2020.

[26] Babamiri BB, Barnes B, Soltani-Tehrani A, Shamsaei N, Hazeli K. "Designing additively manufactured lattice structures based on deformation mechanisms". *Additive Manufacturing*, 46, 1-19, 2021.

[27] Liu P, Liu A, Peng H, Tian L, Liu J, Lu L. "Mechanical property profiles of microstructures via asymptotic homogenization". *Computers & Graphics*, 100, 106-115, 2021.

[28] Baxter G. "Assessing the carbon footprint and carbon mitigation measures of a major full-service network airline: A case study of Singapore Airlines". *International Journal of Environment, Agriculture and Biotechnology*, 7(5), 81-107, 2022.

[29] Gu D, Shi X, Poprawe R, Bourell DL, Setchi R, Zhu J. "Material-structure-performance integrated laser-metal additive manufacturing". *Science*, 372(6545), 1-15 2021.

[30] Sithole C, Nyembwe K, Olubambi P. "Process knowledge for improving quality in sand casting foundries: A literature review". *Procedia Manufacturing*, 35, 356-360, 2019.

[31] Sapkal SU, Patil IC, Darekar SK. *Dimensional Variation and Wear Analysis of 3D Printed Pattern for Sand Casting*. Editors: Yadav S, Singh DB, Arora PK, Kumar H. Smart Innovation, Systems and Technologies, 461-470, India, Springer, 2019.

[32] Pham T, Kwon P, Foster S. "Additive manufacturing and topology optimization of magnetic materials for electrical machines-a review". *Energies*, 14(2), 1-24, 2021.

[33] Wang L, Liu Y, Wang X, Qiu Z. "Convexity-oriented reliability-based topology optimization (CRBTO) in the time domain using the equivalent static loads method". *Aerospace Science and Technology*, 123, 1-20, 2022.

[34] Goh GD, Toh W, Yap YL, Ng TY, Yeong WY. "Additively manufactured continuous carbon fiber-reinforced thermoplastic for topology optimized unmanned aerial vehicle structures". *Composites Part B: Engineering*, 16, 1-10, 2021.

[35] Kartini K, Sipayung GA, Ismail R, Jamari J, Bayuseno AP. "Data transfer analysis of the homogeneous rough surface of a solid model into a CAE system with varying file data formats". *Cogent Engineering*, 9(1), 1-14, 2022.

[36] Karaçam F, Arda ÖC. "Topology optimization of the load-carrying element under a concentrated load". *Trakya Üniversitesi Mühendislik Bilimleri Dergisi*, 22(2), 57-64. 2021.

[37] Merulla A, Gatto A, Bassoli E, Munteanu SI, Gheorghiu B, Pop MA, Bedo T, Munteanu D. "Weight reduction by topology optimization of an engine subframe mount, designed for additive manufacturing production". *Materials Today: Proceedings*, 19(3), 1014-1018, 2019.