Research Article

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# Voronoi Latticed Bike Saddle Design Optimization with Data-Driven Design Technique

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## ABSTRACT

The study presents an innovative methodology using implicit modeling to optimize the design of racing bicycle saddles, focusing on weight reduction while maintaining structural integrity. Implicit modeling addresses the limitations of traditional CAD modeling by defining geometries through mathematical functions, enabling smaller file sizes and more effective analyses for complex models. The research utilized nTopology software to convert a CAD model of a bicycle seat into an implicit model, followed by structural analysis and optimization of a Voronoi lattice structure within the seat. This approach resulted in a significant weight reduction of 50.65%, decreasing the seat's weight from 130.61 grams to 64.45 grams. The maximum elastic displacement measured was 1.65 mm, with the maximum Von Mises stress value observed at approximately 15 MPa, indicating the design's capability to withstand loads. The study concludes that the use of implicit modeling offers substantial advantages in industrial design, particularly in sectors where weight reduction is critical, such as aerospace and automotive. Future research should focus on further developing implicit modeling techniques and exploring their applications in various industrial contexts.

# Veri Odaklı Tasarım Tekniği ile Voronoi Kafesli Bisiklet Selesi Tasarım Optimizasyonu

## ÖZ

Çalışmada, yarış bisiklet selelerinin tasarımını optimize etmek için ağırlık azaltma ve yapısal bütünlüğü koruma odaklı olarak örtük modelleme kullanılarak yenilikçi bir metodoloji sunulmaktadır. Örtük modelleme, geometrileri matematiksel fonksiyonlar aracılığıyla tanımlayarak, daha küçük dosya boyutları ve karmaşık modeller için daha etkili analizler yapılmasını sağlayarak geleneksel CAD modellemenin sınırlamalarını gidermektedir. Araştırmada, nTopology yazılımı kullanılarak bisiklet selesinin CAD modeli örtük modele dönüştürülmüş, ardından yapısal analiz ve sele içerisindeki Voronoi kafes yapısının optimizasyonu gerçekleştirilmiştir. Bu yaklaşım, sele ağırlığının 130,61 gramdan 64,45 grama düşürülmesiyle %50,65'lik önemli bir ağırlık azalması sağlamıştır. Maksimum elastik yer değiştirme 1,65 mm olarak ölçülmüş, maksimum Von Mises gerilme değeri yaklaşık 15 MPa olarak gözlemlenmiş ve bu tasarımın dinamik yüklere dayanma yeteneğini göstermiştir. Çalışma, örtük modellemenin özellikle havacılık ve otomotiv gibi ağırlık azaltmanın kritik olduğu sektörlerde endüstriyel tasarımda önemli avantajlar sunduğunu sonucuna varmaktadır. Gelecekteki araştırmalar, örtük modelleme tekniklerinin daha da geliştirilmesine ve çeşitli endüstriyel bağlamlarda uygulamalarının araştırılmasına odaklanmalıdır.

**Anahtar Kelimeler:** Veri Odaklı Tasarım, Tasarım Optimizasyonu, Kafes Yapılar, Hafifletme, nTopology

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## 1. Introduction

As an innovative design technology, "Implicit Modeling" addresses the shortcomings of the "Boundary Representation" method used by CAD programs [1]. In CAD modeling, 2D sketches are created on a sketch plane, and 3D volumes are generated from them. Even in a simple cube, which is not complex, there are multiple faces, edges, and vertices. As the complexity of the shape increases, the number of these elements also increases. For example, in a unit cell named "Body Centered Cubic," the number of CAD elements can reach up to 42. However, when we aim to create a more complex lattice structure composed of multiple unit cells and periodically replicate this unit cell across three axes in a CAD model, the number of elements and data sizes increase drastically. At a certain point, CAD software may become unable to open these files, or working with them might become impossible. Additionally, since these periodically replicated unit cells have fixed dimensions, it may become impossible to manually optimize the regions where stress is concentrated on a part formed by the lattice structure. At this point, unlike CAD modeling, the same volume can be defined by a mathematical equation through implicit modeling, and the 3D geometry can be rendered as the exact same shape. In this case, implicit data can be stored in very small file sizes, and if the inputs to this mathematical expression change, the geometry generated as the function' s output can also be modified. One of the advantages of implicit modeling is that it enables data-driven design. Since implicit geometry in areas with high stress is data-driven, it can automatically adjust to optimal dimensions if the appropriate input is provided. An example of this method is the adjustment of the distances between voids in a Voronoi lattice and the thicknesses of its struts in such a way that they are variable and optimal according to the stress concentration regions on the part. There are also other significant studies in the literature concerning lattice structures. In some studies, the mechanical properties of parts made of PLA (Polylactic Acid) material produced with different lattice geometries and porosity ratios, as well as the tribological properties of samples made of ASA (Acrylonitrile Styrene Acrylate) material produced with different infill densities, have been compared. It has been found that PLA samples with Octet infill geometry have the highest tensile strength, while Cross infill geometry shows the most deformation [2]. In the ASA material samples, it was determined that those with 90% infill density offered higher hardness values and lower wear rates compared to others [3]. Both studies have demonstrated that parameters such as infill density and geometry are crucial in determining the mechanical and tribological performance of materials. By using topology-optimized parts or complex internal lightweight lattice designs, which are significant advantages of additive manufacturing, current optimization targets such as minimizing material and energy costs can be achieved [4]. The application of these techniques is critically important for sectors like aerospace, medical, and defense, enabling our country to produce competitive projects on an international scale with indigenous and national resources [5].

For instance, recent studies have demonstrated that functionally graded lattice structures (FGLSs) can significantly enhance mechanical properties and energy absorption, particularly when optimized for specific applications, such as in the aerospace and biomedical fields [6]. Furthermore, the design and optimization of gradient lattice structures using advanced CAD techniques have been shown to yield components with improved structural performance and weight efficiency, which are crucial in high-stress environments [7].

Moreover, recent advancements in additive manufacturing, particularly in functionally graded additive manufacturing (FGAM), have highlighted the potential of these methods to create highly customized and optimized lattice structures, providing superior mechanical properties while maintaining lightweight characteristics [8].

One of the main disadvantages of CAD design is that the initial design created by the design engineer is far from the desired objectives, i.e., it is not optimized. The optimization process requires experienced engineers to work on dozens of designs by changing various parameters, resulting in time loss and extra effort, and it is a process that can also be prone to local weaknesses and errors. The implicit modeling technology to be used can create optimal designs where weaknesses are addressed by using field-driven design and data-driven design techniques, analyzing resulting data fields, and using special algorithms.

Recent advancements in the field have also proposed the integration of manufacturing constraints into topology optimization processes, which can significantly enhance the manufacturability of complex

geometries produced through additive manufacturing. This approach not only optimizes structural performance but also ensures that the designs are practical for real-world manufacturing applications, thus providing a more comprehensive solution for the challenges faced in traditional methods [9].
The modeling technique to be used in this study provides a solution to the bottlenecks that will be experienced due to the number of elements in complex lattice structures and indirectly the resulting sizes if designed as a CAD model [10]. As an alternative to periodic lattice structures, the data-driven technique offers the possibility to create the most optimal and extraordinary designs with gradient variations in thickness and variable spatial gaps based on data, representing the most advanced and unique value in the construction field today [11]. Recent studies have also shown that the material properties of functionally graded lattice structures can be fine-tuned to achieve specific mechanical behaviors, making them suitable for a wide range of industrial applications, especially where weight reduction and mechanical efficiency are crucial [12]. This study will gain the ability to create strong lattice structures that can safely operate within certain boundary conditions where high-level lightness is desired and using this method for redesigning currently used parts in our strategic sectors will pave the way for establishing university-industry collaborations with institutions like TEI, which is of critical importance [13].

## 2. Method

This study describes a methodology that can be used to lighten a racing bicycle seat by leveraging the advantages of implicit modeling using nTopology software. This methodology initially requires a CAD model as input. Final design modifications to the reference CAD model were completed using SOLIDWORKS software. The reference CAD model in the study is an assembly file of the bicycle seat itself and its lower supports and was imported into the software with the "Import Part" function block. The internal and external edge features in the CAD model of the bicycle seat were defined as variables to be used as inputs in other functions at intermediate stages of the methodology. Figure 1 below shows the CAD model of the bicycle seat and its lower supports from different angles and an isometric view of the edges defined as variables.

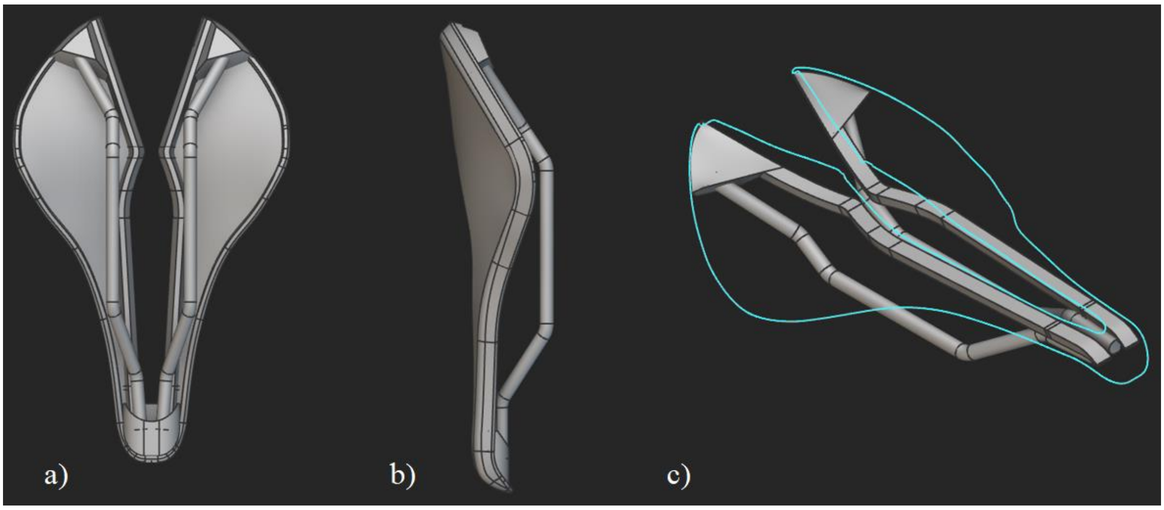

Figure 1. Reference CAD Model and Support Structures in Various Perspectives (a,b and c)

Various function blocks belonging to the nTopology software accept different data types as input. However, some functions used to optimize the CAD model require implicit data as input. For this reason, the CAD data type imported into the software was converted to the implicit data type with the "Implicit Body from CAD Body" function block. Figure 2a below shows an image of the implicit volume that does not contain the elements of the CAD modeling method using the "Boundary representation" method. To perform data-based optimization on the Voronoi lattice structure used in lightening the seat, the data obtained from the structural analysis of the seat should be used [14]. To create the mesh required for structural analysis, several intermediate processes were completed. In this process, a mesh was obtained from the implicit body. The mesh created with the "Mesh from Implicit Body" function block was used as input in the "Remesh Surface" block to create a surface mesh suitable for structural analysis, and a new mesh structure was obtained as an output of this function by adjusting the relevant parameters. Different mesh parameters affect mesh metrics such as skewness and orthogonality, so different parameters should be used for different geometries. Figure 2b below shows the new surface mesh created for structural analysis. Figure 2c shows the use of the surface mesh arranged as input for a function that can create a volume mesh, and to generate compatible volume mesh elements, the edge length parameter of the volume mesh elements was taken equivalent to the edge length parameter of the surface mesh elements [15]. After creating the volume mesh, nodes were assigned to obtain a finite element volume mesh suitable for structural analysis.

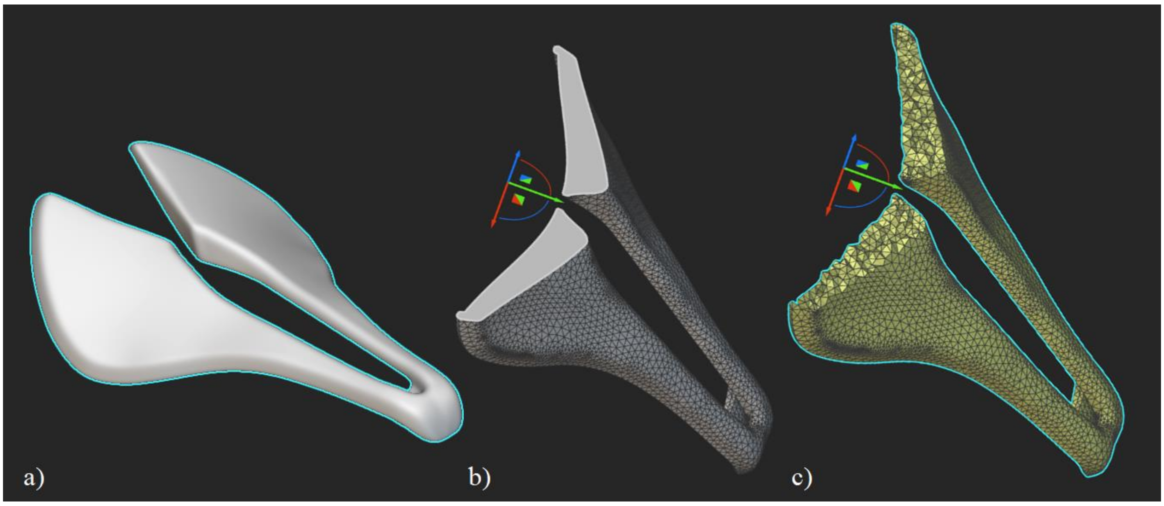


Figure 2. a) Implicit Body b) Surface Mesh c) FE Volume Mesh

Another element necessary for structural analysis is the definition of boundary conditions. In this study, when the right and left regions of the seat model are considered together, a distributed force of 250 N in the -Z axis was applied to two circular areas, each approximately 30 mm in diameter. The applied forces are represented by yellow arrows in Figure 3a. In Figure 3b, the fixed faces defined by restricting translational and rotational movements are represented by red cones. The locations of the cones and arrows correspond to the positions of the nodes on the mesh.

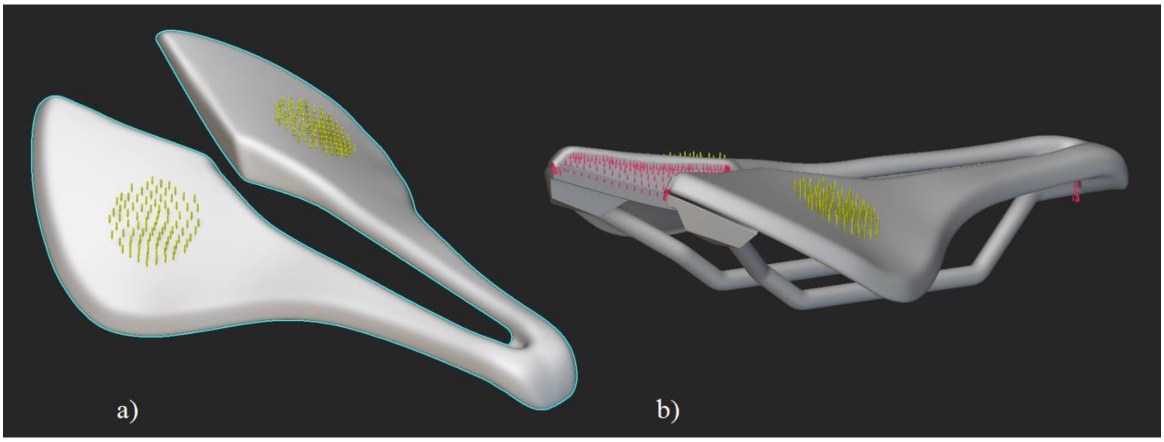


Figure 3. a) Applied Forces b) Fixed Faces

Figure 4a below shows the gradient color change from blue to red, representing the maximum displacement. Considering the defined Polyamide PA2200 material and other boundary conditions, the amount of elastic displacement increases as we move away from the fixed faces with the support structure. The mesh frame visualized here, which contains a relatively small number of mesh elements, was not used in the static analysis. This mesh frame, with 13,710 nodes and 57,217 mesh elements, was used to obtain the point map necessary for generating the optimized Voronoi lattice. Figure 4b below shows the point map exported as an output of the structural analysis function. As a result of identifying the displacements and completing the intermediate processes where the obtained point map is used as input in different functions, an implicit field to be used for developing the Voronoi lattice was derived.

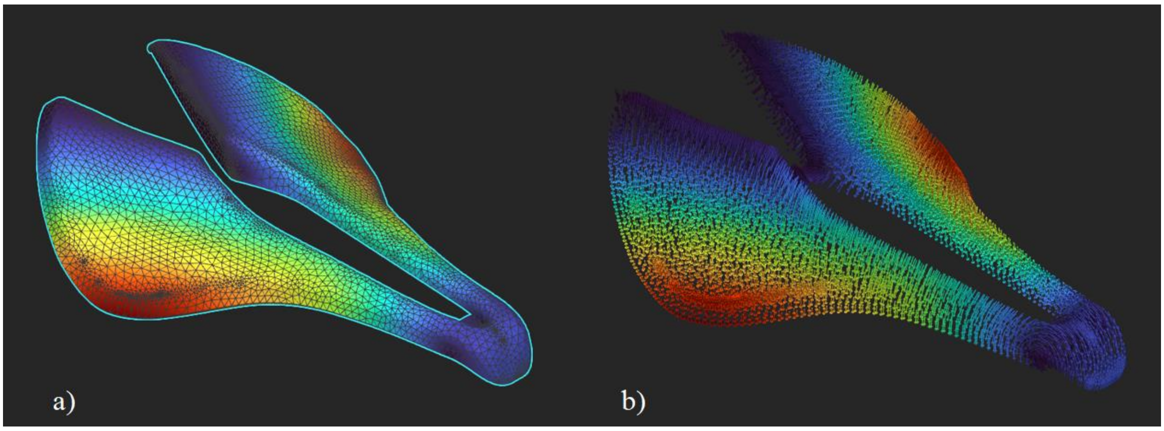


Figure 4. a) Displacements b) Point Map

Figure 5a below illustrates the mesh parameters used in the static analysis to obtain the point map required for generating the optimized Voronoi lattice. The edge length of the surface mesh was set to 3 mm, and the mesh element size was kept large, resulting in a coarser mesh. This approach allowed for a shorter analysis time while still providing sufficient accuracy to obtain the necessary point map. A "Triangle" form mesh element was used for the surface mesh, and a volumetric mesh with the same edge length was derived. Figure 5b below presents the mesh parameters used in the static analysis of the final design. Specifically, the edge length of the mesh elements was reduced, and the number of mesh elements was increased. Mesh metrics were monitored, and optimal values were selected for other parameters to achieve a mesh of sufficient quality for use in the part's analysis.

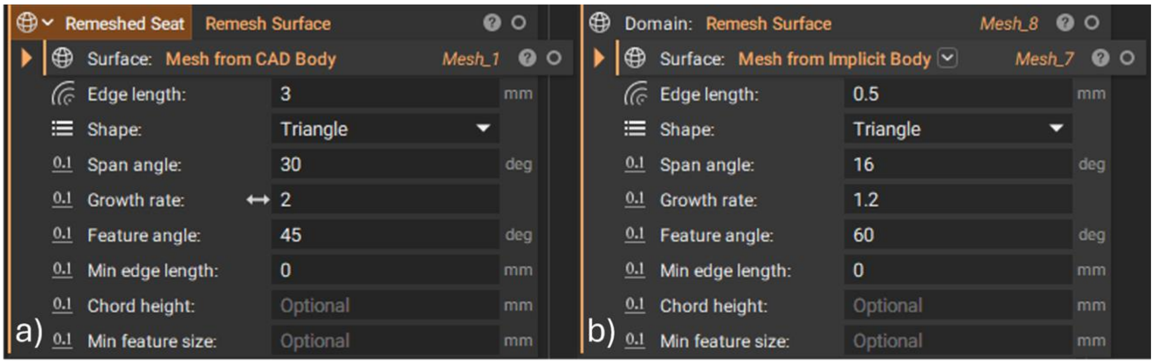


Figure 5. a) Mesh Parameters to Obtain Point Map b) Mesh Parameters for Static Analysis of Voronoi Seat

In creating the implicit field, the "Field from Point Map" function block, where parameters such as interpolation and extrapolation are also adjusted, was used. Functions manipulating the implicit geometry at locations corresponding to the scalar magnitudes contained in the implicit field were utilized [16]. To create the Voronoi lattice in the volume where it will be modeled, the "Random Points in Body" function block, which uses the Pseudorandom Number Generator algorithm at its core, was used to create a stochastic arrangement at the center points. Data-based optimization was performed in the random arrangement using the implicit field, and instead of fixed scalar values for the gaps between the center points, gaps with a gradient transition and variable distances were obtained. Similarly, the thicknesses of the beams forming the Voronoi lattice were also manipulated using the implicit field, achieving the desired gradient transition [17]. As a result, since the surface mesh was also used as a variable in the parameters of the function block forming the Voronoi lattice, a data-based optimized lattice design limited by the surface and fully compatible with it was obtained. Figure 6a below shows the optimized Voronoi lattice. In Figure 6b, the passive regions forming the outer frame of the designed Voronoi seat, which are not in lattice form, are shown in blue.

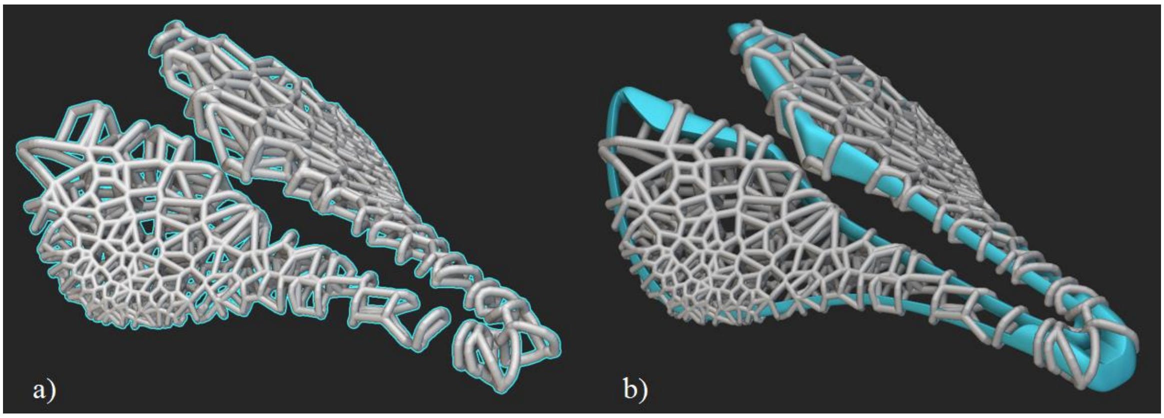


Figure 6. a) Improved Voronoi Lattice b) Passive Zones

In creating the passive regions represented in blue, the edge features and CAD faces referenced from the CAD model of the seat were used. It is important that the offsetting process performed to create solid regions designed based on the CAD faces at the front and rear parts of the seat does not exceed the volumetric boundaries of the seat geometry. Similarly, internal and external edge features also require offsetting after being converted to the implicit body, and it is important that the resulting geometries do not exceed the volumetric boundaries of the seat geometry. Figure 7a below shows the parts where the Voronoi lattice exceeds the volumetric boundaries of the seat. In a seat that can be produced from a rigid material like polyamide, this situation is not acceptable as it can completely eliminate comfort conditions. This issue was resolved by clipping the geometries created by offsetting only in the regions where they intersect with the internal volume of the seat geometry. When this clipping process used for designing the passive regions is also applied to the Voronoi lattice, a smooth surface fully compatible with the seat geometry was obtained, and the result of this process is seen in Figure 7b.

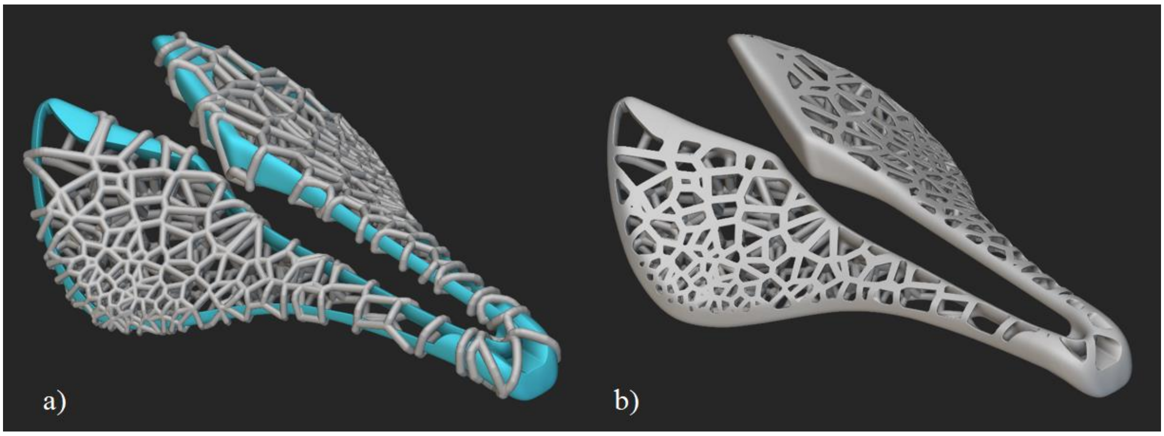


Figure 7. a) Before Trimming b) After Trimming

Figure 8 below shows the optimized seat geometry, lower supports, and the gradient color change representing the geometric change resulting from the analysis in the Voronoi lattice together. The static analysis was completed by defining the relevant parameters within the "Static Analysis" function block, which is natively available in nTopology software.

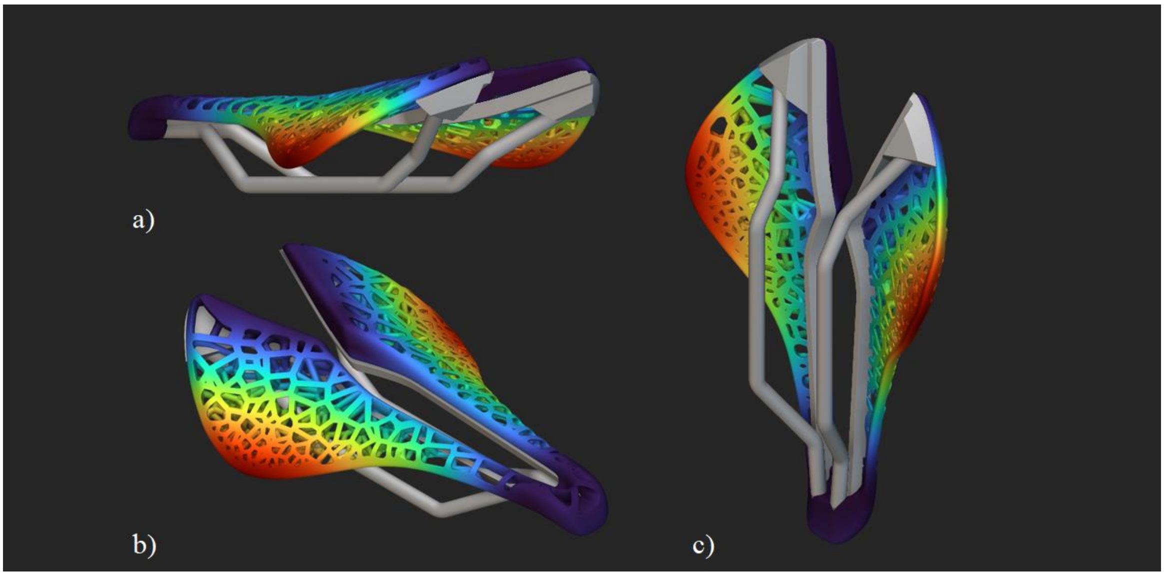


Figure 8. Various perspectives (a, b and c)

## 3. Results and Discussion

In Figure 9 below, the 'Finite Element Volume Mesh' prepared for the static analysis is shown. The mesh consists of 26,039,096 elements and 5,467,823 nodes. To prevent deviations in the analysis results due to insufficient mesh and node counts, the analysis was completed by generating a high number of mesh elements and nodes.

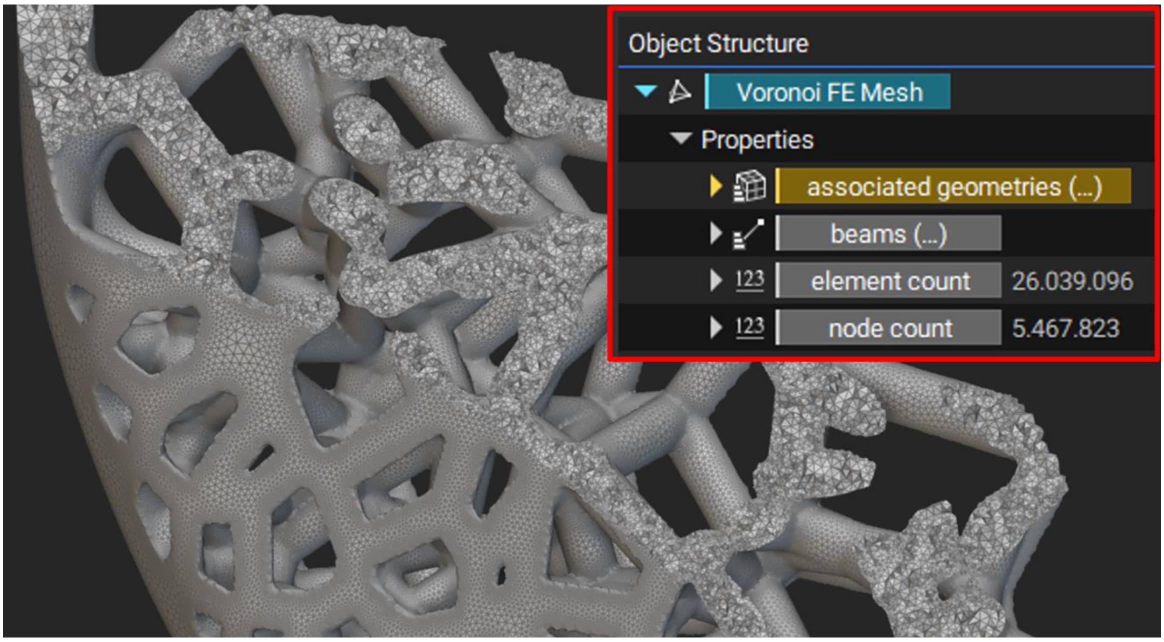


Figure 9. Finite Element Volume Mesh (Element Count and Node Count)

Figure 10a below shows the skewness, one of the mesh quality metrics. The skewness quality can be determined based on its values ranging from 0 to 1. A skewness value close to 0 is desired. Values between [0-0.25] are considered 'excellent', [0.25-0.50] are 'very good', [0.50-0.80] are 'good', [0.80-0.94] are 'acceptable', [0.95-0.97] are 'poor' and [0.98-1.00] are 'unacceptable'. The average skewness value of the mesh for the part is 0.2868, and the skewness values for all mesh elements are visualized using a color gradient. Considering the entire mesh, the skewness metric is rated as 'very good'. Figure 10b below shows the orthogonality, another mesh quality metric. The orthogonal quality can be determined based on its values ranging from 0 to 1. An orthogonal quality value close to 1 is desired. Values between [0.95-1.00] are considered 'excellent', [0.70-0.95] are 'very good', [0.20-0.69] are 'good', [0.15-0.20] are 'acceptable', [0.001-0.14] are 'poor' and [0-0.001] are 'unacceptable'. The average orthogonality value of the mesh for the part is 0.8761, and the orthogonality values for all mesh elements are visualized using a color gradient. Considering the entire mesh, the orthogonality metric is rated as 'very good'.

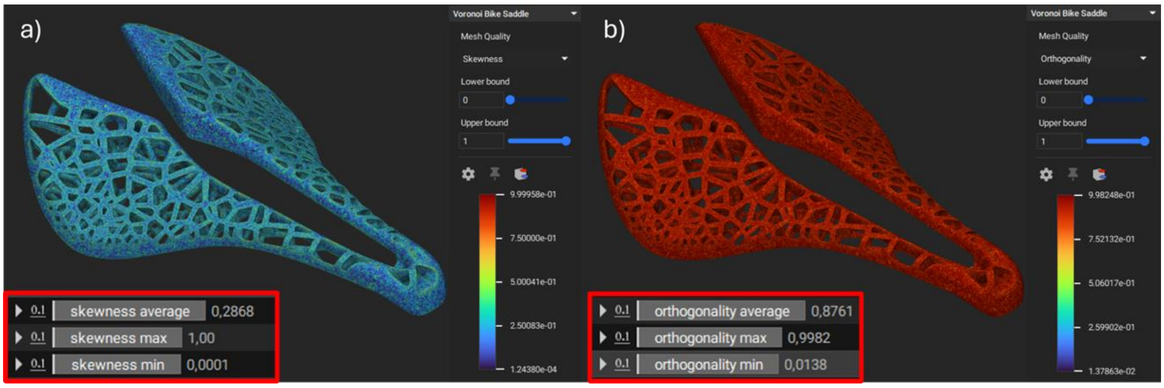


Figure 10. Mesh Metrics a) Skewness b) Orthogonality

In Figure 11a below, when examining the color spectrum resulting from the analysis on the part, it is believed that the stresses are well-distributed across the part. When looking at the minimum and maximum Von Mises stress values, it is observed that the maximum stress value is at the limit of 60 MPa, which is the tensile strength of the selected polyamide PA2200 material. However, the localized value observed here may be misleading. The localized value shown in Figure 11b has resulted from a divergence occurring at a node where a 'mesh singularity' has taken place. To better analyze the stresses, the color spectrum should be adjusted, and the distribution of stresses on the part should be re-examined.

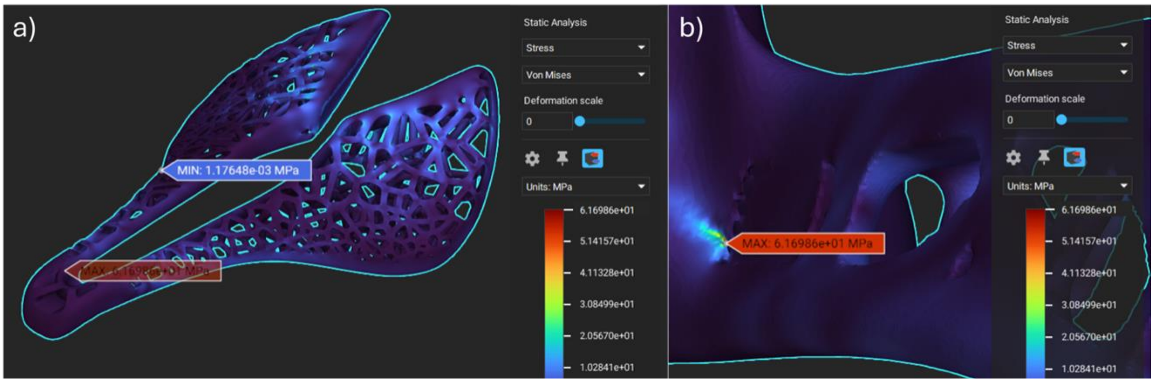


Figure 11. a) Minimum and Maximum Von Mises Values [MPa], b) Mesh Singularity at the Maximum

As seen in Figure 12a below, the color spectrum initially ranges from 0 [MPa] to 60 [MPa]. When the maximum value displayed in the spectrum is reduced from 60 [MPa] to 15 [MPa], as shown in Figure 12b, the sections that are critical under load become much more apparent. The sections with stress values closest to 15 [MPa] and other sections with high stress values are primarily located in the thick beams of the Voronoi lattice and at a few of their corner points. It is observed that the stresses along the cross-sections of the thick beams are generally low. In this case, the safety factor is approximately, and at least, 4, indicating that it is likely to withstand variations in dynamic loading.

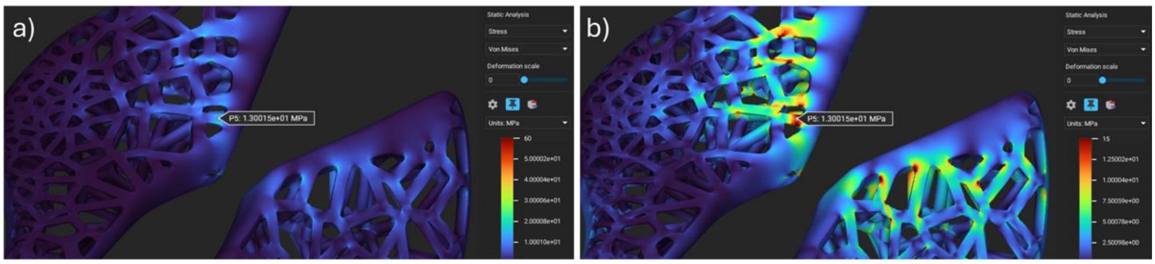


Figure 12. Change in the color spectrum (from 60 MPa (Figure 11a) to 15 MPa (Figure 11b))

As seen in Figure 13 below, the maximum deformation occurred at the furthest point of the seat. It was observed that the maximum displacement value at this location, where elastic deformation occurred, is 1.65 mm.

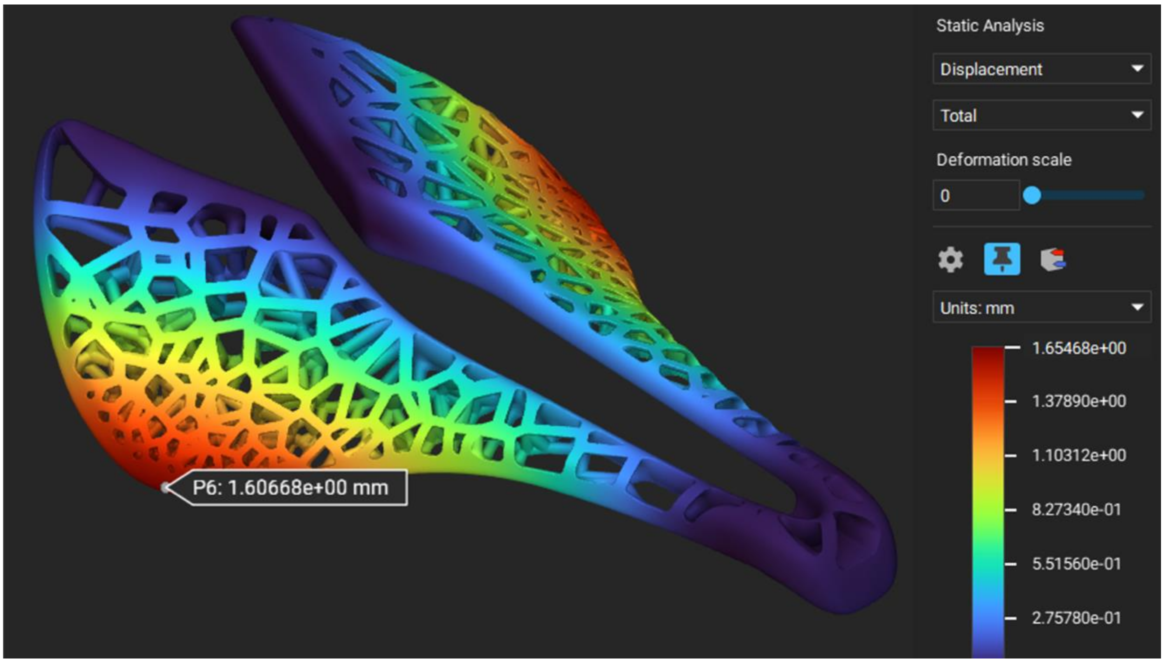


Figure 13. Maximum Displacement [mm]

In Figure 14 below, the weight information of the original design of the seat taken as a reference is 130.61 grams, and the weight information of the optimized Voronoi lattice seat design is 64.45 grams, given separately. The weight gain compared to the original design is 50.65%, achieving a gain of half.

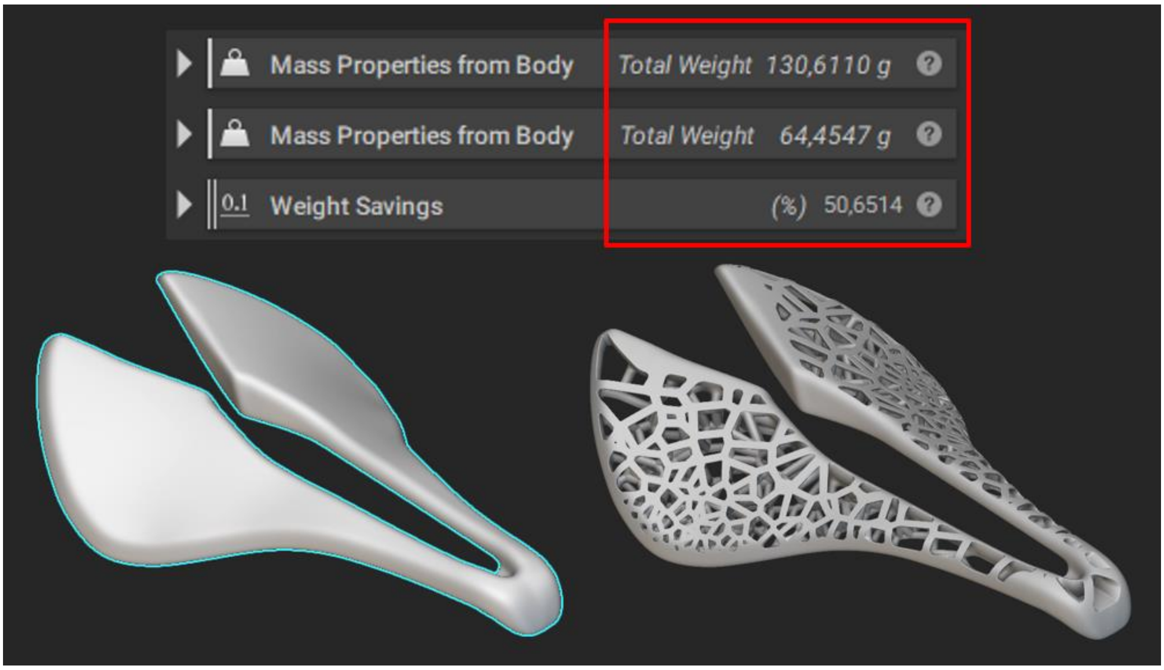


Figure 14. Total Weight and Weight Savings Ratio

## 4. Conclusion

In this study, a methodology developed using nTopology software to reduce the weight of racing bicycle saddles has been presented. The study initially involves taking a CAD model as input and subsequently optimizing this model using the "Implicit Modeling" method within the nTopology software. Instead of the boundary representation of the CAD model, implicit modeling, which uses geometries defined by mathematical functions, allowed for the data to be stored in smaller file sizes and enabled effective analysis despite the complexity of the model.

In the static analyses conducted, the maximum elastic displacement value for the saddle designed with PA2200 polyamide material was measured as 1.65 mm. This displacement occurred particularly at the farthest point of the saddle surface, facilitating the analysis of stress concentrations in the Voronoi saddle. The results obtained indicate that the combination of the selected material and geometry can operate safely within certain limits. Furthermore, the maximum stress value observed in the critical sections as a result of the Von Mises stress analysis was determined to be around 15 MPa. However, it was also considered that a point value appearing as 60 MPa could be misleading, possibly resulting from a local "mesh singularity."

Additionally, it was found that the Voronoi lattice structure used in the study is highly effective in both reducing structural weight and maintaining mechanical strength. As a result of the optimization, the weight of the saddle design was reduced by 50.65%, from 130.61 grams to 64.45 grams. This significant weight reduction technique could offer a major advantage, especially in sectors such as aerospace and automotive, where weight reduction is crucial. Furthermore, it is believed that the generally low stress distributions observed in the cross-sections of the thick beams of the saddle could enhance the design's durability against dynamic loads.

The methodology used in this study is also thought to provide significant advantages in the industrial design processes by integrating complex geometries into the production process. Particularly, the combined use of parametric modeling and implicit modeling methods offers flexibility in the design process while also considering manufacturing constraints. These approaches enable the creation of geometries that are difficult to achieve with traditional CAD modeling methods. Moreover, the applicability of this methodology in other engineering fields suggests that the study could have a broad impact in both industrial and academic domains.

In future studies, further research and development of implicit modeling techniques should be pursued, along with testing and adapting the methodology for different industrial design applications, conducting more detailed experiments to increase the accuracy of the analyses, and further investigating how implicit modeling can be used in other industrial applications. The literature contains example studies on how it can be utilized in various industrial design applications. One such example is the design of a heat exchanger composed of gyroid unit cells using the implicit modeling technique. Gyroid unit cells have a wall that can separate the cold and hot fluids, thereby enabling heat transfer through the thin-walled gyroid unit cells [18]. In another study, a jet engine bracket was optimized using a variable lattice structure and was able to maintain its strength under the defined boundary conditions according to the static analysis results. Implementing these recommendations can enable a broader range of applications for implicit modeling and improve industrial design processes.

In conclusion, implicit modeling techniques stand out as an effective tool in meeting the requirements for weight reduction and structural optimization. The method presented in this study could offer important opportunities for university-industry collaboration, particularly in the redesign of parts used in strategic sectors. In this context, collaborations with critical institutions such as TEI could contribute to our country's ability to produce internationally competitive projects.

## Acknowledgment

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## Conflict of Interest Statement

The authors declare that there is no conflict of interest

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