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OPTI-WAFFLE: A TECHNOLOGICAL FURNITURE DESIGN AND MANUFACTURING MODEL

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Abstract: Parametric design allows the use of computers and systems that can make decisions beyond human capacity, such as machine learning, through optimization in design and manufacturing. From this point of view, it is aimed to shape and manufacture the design by minimizing the subjective decisions of the designers by using various algorithmic methods and structural optimization to provide ergonomics in a furniture design. As the subject of the study, a meeting table for 8 people was discussed. In the process, 'artificial intelligence supported inspiration board', 'parametric design', 'human-computer interaction and sensors', 'topology optimization', 'observation in augmented reality' and 'computer-aided manufacturing' techniques were used sequentially. After the assembly was completed, the product obtained was finally evaluated in terms of structure-function relationship.

Keywords: Parametric design, Topology optimization, Waffle structure, Computer-Aided ergonomics

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1. Introduction

Architectural design and manufacturing research are diversifying and moving in new directions. Changes in technology, such as new materials, design methods, and construction techniques, are accelerating the need to advance and integrate design knowledge across disciplines. In design disciplines, the transition from computer-aided design methods to parametric design models enables designers to create more efficient and optimized designs, make decisions that are beyond the capabilities of humans through the use of machine learning and control manufacturing decisions through the digitization of production techniques.

The primary objective of the study is to develop a model that minimizes the subjective decisions of designers by utilizing various algorithmic methods in furniture design to shape the final product. The focus of the study is the design of an eight-person conference table. As the table size, a volume of 240*120 cm with a height of 72 cm has been selected according to anthropometric average scale. In production, the use of MDF plates measuring 120*80 by 1.8 cm has been selected. These decisions are the designer's most influential subjective parameters in forming the model. Structural Topology Optimization (STO) is a computational design methodology that employs mathematical algorithms to optimize the distribution of material within a predefined space, subject to constraints and performance objectives, in order to create structurally efficient forms, typically realized via techniques such as Finite Element Analysis and various optimization algorithms. STO technique has the greatest influence on the design's outcome, out of the numerous algorithmic techniques employed in the study. This article does not invent any of the techniques utilized in the procedure. The unique aspect of this study is the development of an algorithmic model independent of the subjective decisions of the designer through the use of algorithmic methods in furniture design, with the combination of the techniques used in the planned order.

1.1. Literature Review

Due to the structure of parametric design, it is now possible to digitize the design action and optimize design decisions autonomously, allowing computers to make decisions automatically during the design process. Parametric design is central to the techniques applied in this study. Analytical algorithm-based design is the cornerstone of parametric design. Greg Lynn, one of the pioneers of parametric design, developed a computational approach to architectural design that employs digital tools and algorithms to create complex and difficult-to-design-and-implement outcomes (Lynn, 1998, 1999). Although "form follows function" was first proposed by early modernists, this phenomenon is literally realized in parametric design (Schumacher, 2009, 2011). The parameters that give parametric design its name define the function(s), and designers can transform various contextual data into form-giving elements. Parameters and algorithms form the basis of this study, which also shapes the design.

Although furniture design does not have a long history of artificial intelligence-supported optimization methods, ZHA CODE's ACADIA chair is one of the establishing approaches in this field (Schumacher, 2017). Since production of models designed with topology optimization is better suited for 3D printing, an additive technique, the majority of current research is conducted accordingly (Kazakis et al., 2017; Ma et al., 2021; Cui et al., 2022).

Machine Learning is the fundamental computing field that enables visual synthesis, a technique used in the preliminary design phase. Processing data with reward and punishment logic via Artificial Neural Networks (ANN) (Jain and Mao, 1996), reading, understanding, and imitating human language via Natural Language Processing (NLP) (Nadkarni et al., 2011), and identifying and labeling objects via Computer Vision (Vinyals et al., 2015) all contribute to complex learning capability. Visual synthesis dates back to the ELIZA program at the MIT Artificial Intelligence Laboratory in the 1950s (Agassi and Wiezenbaum, 1976), but until recently, the ability to generate realistic images was limited. The development of Deep Convolutional Generative Adversarial Networks (DCGANs) (Goodfellow et al., 2014) represents the most significant milestone in the method's evolution. Text-to-3D model synthesis is an additional promising research area linked to image synthesis (Jain et al., 2022; Liu et al., 2022; Zhuang et al., 2023).

In the parametric design phases of the research, Rhinoceros – Grasshopper was utilized as software. According to Rutten, Grasshopper is the most effective program for parametric design and parametric architecture (Rutten and McNeel, 2007). Grasshopper's visual coding (visual scripting) or node-based programming structure, which is more perceptible to designers, allows for the optimization of generative designs (Davis and Peters, 2013). In addition, numerous researchers have created over 650 Grasshopper plugins (Food4Rhino, 2023). Thus, modeling, analysis, simulation, optimization, real-time responsiveness, and numerous other domains can be interacted with using the same interface.

The main solid design process of the study starts with Human-Computer Interaction (HCI). HCI is the technique used at the beginning of the parametric design process. It is the study of how people interact with technological devices and software (Eloy et al., 2016). This field aims to make technology useful to people and enable them to interact effectively with technological devices. Sensors are the fundamental tools for human-computer interaction. Kinect, which was used in the study, is a sensor that can be programmed using an open-source software development kit; as a result, it is utilized in research in a variety of fields (Lun and Zhao, 2015).

The main form-giving process to the study, Structural Topology Optimization (STO) is a form optimization method that employs machine learning models to optimize the arrangement of materials within a user-defined area for a particular set of loads, conditions, and constraints (Halle et al., 2021; Rade et al., 2021). STO optimizes the performance and efficiency of the design by eliminating unnecessary materials from areas that do not need to carry significant loads in order to reduce weight. Although STO is currently computer-assisted, its origins date back to 1904 (Michell, 1904). Over time, the method has evolved, algorithms for numerical environments have been developed (Zhou and Rozvany, 1991), and it continues to be developed in accordance with contemporary technologies (Cui et al., 2022; Wynne et al., 2022). Aerospace (Niemann et al., 2013), automotive (Bikas et al., 2015), and medicine (Sun et al., 2019) are the primary applications for STO. In these fields where lightweight construction is essential, STO provides significant advantages. Although there are numerous alternatives to STO software (Tyflopoulos and Steinert, 2022), there are a few that stand out for the use in architecture.

The next process of the study is waffle structures. In this study, waffle structure, more specifically defined as interlocked planar slicing, is a modern manufacturing technique. The production method, named after the pattern on the food item "waffle," is formed by slicing the two planar dimensions of a defined volume at precise intervals. The most well-known architectural example of waffle structures is the Parasol building in Seville (Schmid, 2010). Waffle structure is employed not only at the building scale, but also at smaller scales, such as in pavilion and furniture design (Indrawan, 2016; Dumitraşcu et al., 2018).

Augmented Reality (AR) is the real-time display of digital data superimposed on images of the real world. AR technology is utilized in numerous industries, including design, education, and entertainment. The fundamental distinction between Virtual Reality (VR) and Augmented Reality (AR) concepts is that in VR, the subject visually detaches from their physical location using a tool to experience a computer-generated virtual environment. AR, on the other hand, 'enhances' the user's perception of the real space around them by superimposing virtual objects. In contrast to virtual reality, in which the user is completely immersed in a computer-generated virtual environment, augmented reality superimposes virtual objects on the image of the real world that the user sees (Milgram and Kishino, 1994). Therefore, unlike VR, AR augments rather than alters reality.

The final technology used in the study is Computer-Aided Manufacturing (CAM). Today, CAM technologies are widely employed in the industrial sector. These systems allow the manufacturing process to be carried out quickly and efficiently while simultaneously enhancing the quality of the product. Various industries use computer-aided manufacturing technologies, including the automotive, aerospace, medical device, and defense industries (Bickel et al., 2018). There is a procedural parallel between design thinking, physical models, and information in these fields. In conjunction with the digitalization of manufacturing and fabrication techniques, designers are developing new ways of thinking (Arpak et al., 2009). With this strategy, computer-aided use of machines such as CNC, laser cutting, and 3D printers are anticipated to shape the architecture of the future via mass customization-based production methods.

Forms derived from STO are typically manufactured using additive manufacturing techniques, such as 3D printing, as they are not particularly difficult to produce conventionally. This disadvantage of STO is eliminated through the adaptation of STO-obtained forms to waffle structure manufacturing, which will be explained in the following section. In architectural concept studies, STO and waffle structure are frequently combined (Bañón and Raspall, 2021). However, in these studies, the structure is formed using optimization techniques based on surface tension, and there is no volumetric three-dimensional optimization. Combining structural topology optimization and waffle structures in furniture design, this research fills a void in the field of study.

In light of the evolving paradigms in furniture design and manufacturing, this study introduces a theoretical framework that centers on the integration of STO and waffle structures. This framework's attempt to automate the design process while achieving mass customization and material efficiency is innovative. It integrates design knowledge from diverse technological domains, such as machine learning algorithms and augmented reality, to create an innovative and effective workflow. The framework aims to overcome traditional design constraints by leveraging computational tools that complement human intuition and creativity. This synergistic approach not only increases the effectiveness of the design process, but also pushes the limits of customization and sustainability in furniture design.

2. Materials and Methods

In the design process, sequential techniques such as 'artificial intelligence-aided mood board', 'human-computer interaction', 'parametric design', 'topology optimization', 'observation in augmented reality', and 'computer-aided manufacturing' have been utilized (Figure 1).

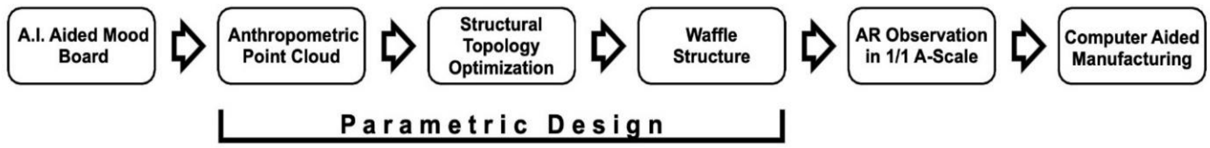

Figure 1. Design Process Procedure.

Initially, a brainstorming board was created using AI algorithms that perform visual synthesis. Then, instead of subjective design decisions, it was planned to develop the product of design decisions obtained through coding using parametric design methods. The parametric design scenario which is executed through the Rhinoceros Grasshopper plugin, begins with the collection of anthropometric data of the volume defined by the user's feet and legs using sensors to generate a point cloud. Then, this data was defined as a void in the topology-optimized structure of the parametric design environment. The mass formed as a result of topology optimization has been converted into an interlocked planar sliced structure using parametric design methods, and the resulting design has been experienced in augmented reality at a scale of 1/1. Using computer-aided manufacturing software, cut drawings were obtained, and the obtained drawings were checked and adapted to be manufactured on a CNC machine, and the assembled table was then evaluated.

3. Results and Discussion

3.1. Image Synthesis

At the outset of the research, algorithms that perform visual synthesis (text-to-image generation) were used to create a mood board and explore potentials. The terms 'meeting table,' 'parametric design,' 'topology optimization,' and 'waffle structure' were used as text in the application of these algorithms. The terms were entered as keywords, not to describe a specific design. Thus, it was desired that artificial intelligence's adaptability and creative synthesis yield an objective benefit.

The purpose of this technique is not to visualize a table in the mind of the designer using artificial intelligence, but rather to be inspired by the various visual syntheses of artificial intelligence. Not only was a single platform utilized, but also popular platforms such as Midjourney, Dall-E, Leonardo, DiffusionBee, Microsoft Designer, MotionLeap, Bluewillow, and FreewayML are used. Examining the results, it became evident that artificial intelligence typically evaluates waffle shape figuratively (Figure 2).

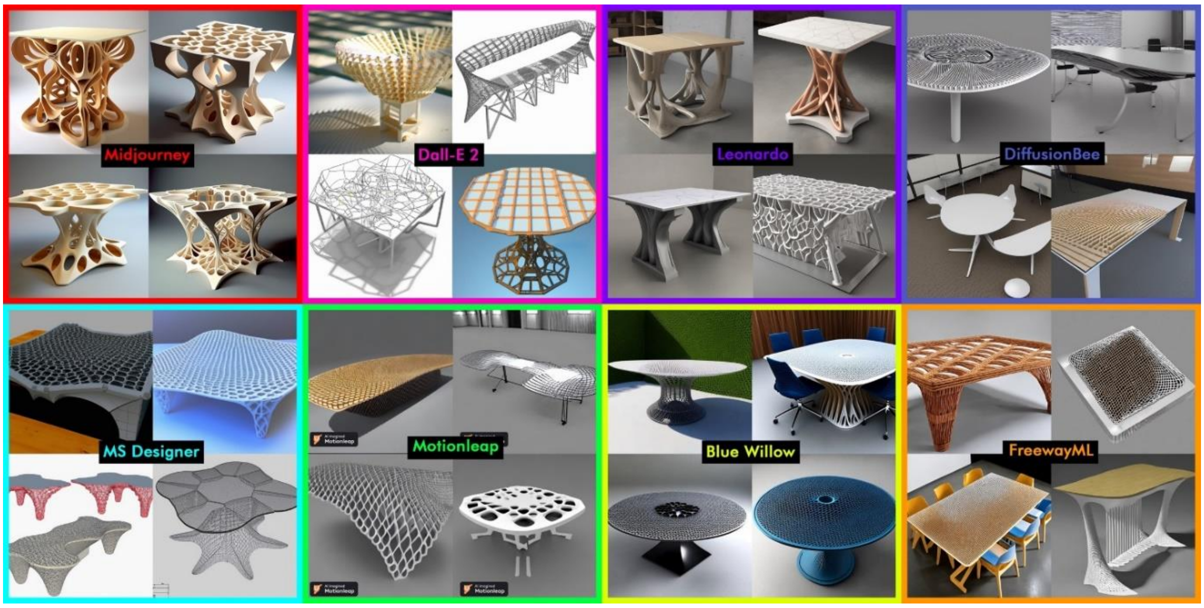

Figure 2. Visualizations created by various artificial intelligence systems utilizing the terms "table, waffle structure, parametric design, and topology optimization".

Aesthetically, Midjourney's visuals are far superior to Leonardo's, which are more realistically implemented. Blue Willow observed (top right) a single image containing the most appropriate visual for the imagined design. Nevertheless, it should be emphasized that this stage involves eye gymnastics. Even if it has no direct effect on the design, algorithms created with artificial intelligence enable the visualization of multiple variations by creating a mood board during the pre-design phase.

3.2. Parametric Design Environment

In a parametric design environment, the processes of transferring anthropometric data to design, topology optimization, and shaping waffle structures have been conceived. In conventional designs, performance-oriented decisions are made according to the following procedure: a design is created, the model is simulated, evaluation and improvement are made, the improved method is re-simulated, and this cycle continues until certain criteria are met. However, in designs created with algorithmic methods, simulation and parameter changes can be automated using various machine learning methods, allowing for the system's maximum efficiency to be realized. In the developed Structural Topology Optimized-Waffle model, parameters such as final dimensions, empty volume, loads, and support points are defined. By controlling the above-mentioned parameters within a single software, the designer's subjective decision-making is minimized, and all these decisions and parameter changes can be observed in real time. The study utilizes the Millepede add-on of the RhinoCeros 6.0 software to implement the technique of structural topology optimization. In the following three sections, the hardware and software utilized in the parametric design environment are discussed more deeply, as well as the parameters.

3.3. Anthropometric Point Cloud

In the project, using the Kinect sensor, the foot and leg positions of three different heighted users were recorded at various times while working at a table, as well as their anthropometric data. The obtained point clouds from the recorded positions were combined to create a three-dimensional map of the action (Figure 3).The boundary of the cloud has been delineated by a curve comprised of over ten million points, which was then sectioned.

The purpose of rotating the section line derived from the point cloud to the table's perimeter is to improve ergonomics. Subtracting the volume of use created by the section line from the total volume of 240*120*72 cm, the volume limit of the table design is determined (Figure 4).

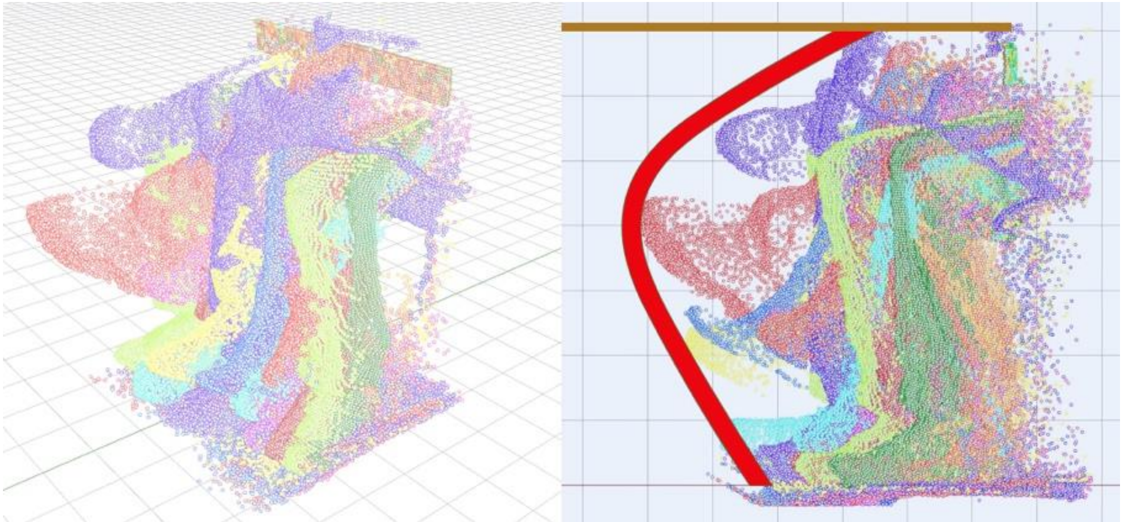

Figure 3. Point Cloud. (left) Sensor-obtained points; (right) section line derived from the point cloud.

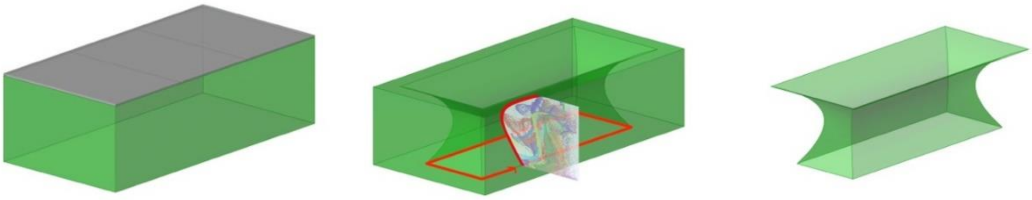

Figure 4. Volume definitions, (left) Total volume of 240*120*72 cm; (center) Volume defined by rotating the usage section curve around the table's perimeter; (right) Final design boundary.

3.4. Structural Topology Optimization

STO was used to design the table's fundamental shape. Taking into account the space and functions where the table will be used, as well as the fact that it will be subject to significant physical deformation and be frequently rearranged, the table's top has been designed in three sections. In production, MDF plates measuring 120 x 80 x 1.8 cm are planned. The three 120 x 80 cm tables will be attached to the substructure using L-profiles at the red points shown in Figure 5. In the topology optimization algorithm, it has been programmed that the load will be applied from these connection points, as load transfer will occur from these points. There are also vectors in the horizontal axis, as loads are not only in the -Z axis but also take into account that there will be lateral leanings from the load points toward the table's center of gravity. Figure 5 depicts the design volume, load, and support data entered into the STO algorithm.

In STO, "volume fraction" refers to the ratio of material volume to total design domain volume, which serves as a constraint for balancing structural performance and material efficiency. Masses obtained with different volume fractions and resolution parameters can be compared in Figure 6. When STO is conceived for objects created with the additive method, 3D printing, and the volume ratio is typically between 0.10 and 0.20. However, since the volume emptying in the waffle structure method that will be used after this stage will be much larger, the excessive volume fragmentation caused by these volume fractions compromises the structural integrity. Examining STO derivations, it has been subjectively predicted that the iteration with a volume fraction of 0.35 and a resolution of 70 will be appropriate for waffle structure construction. Examining the formation process of the iteration, it has been predicted that a resolution value of 70 will result in a more rigid structure (Figure 7).

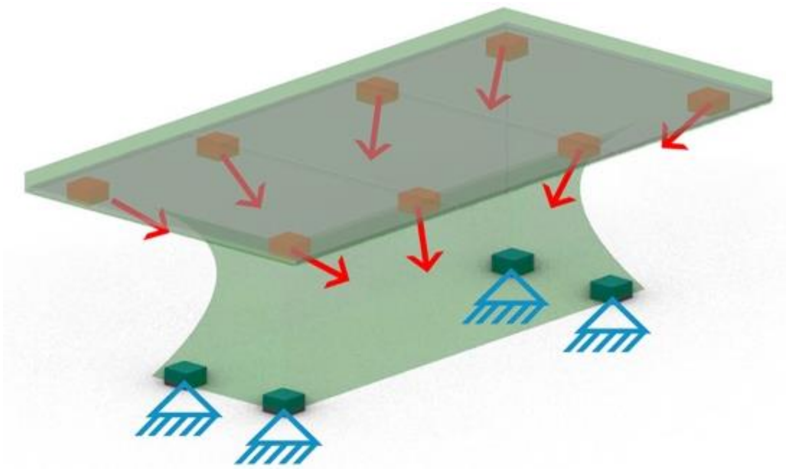

Figure 5. Volume specified in the tOpos plugin (green), loads (red), and supports (blue).

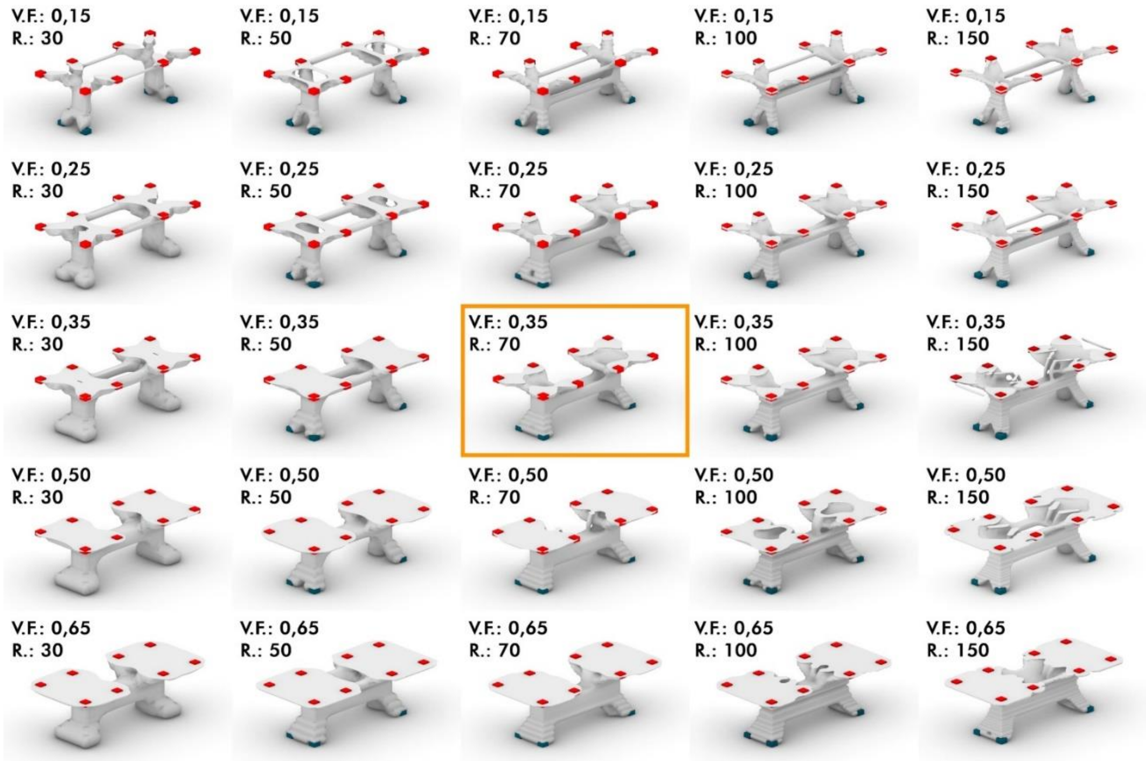

Figure 6. Different optimization parameter results and selected iteration (orange), V.F.: Volume Fraction, R.: Resolution.

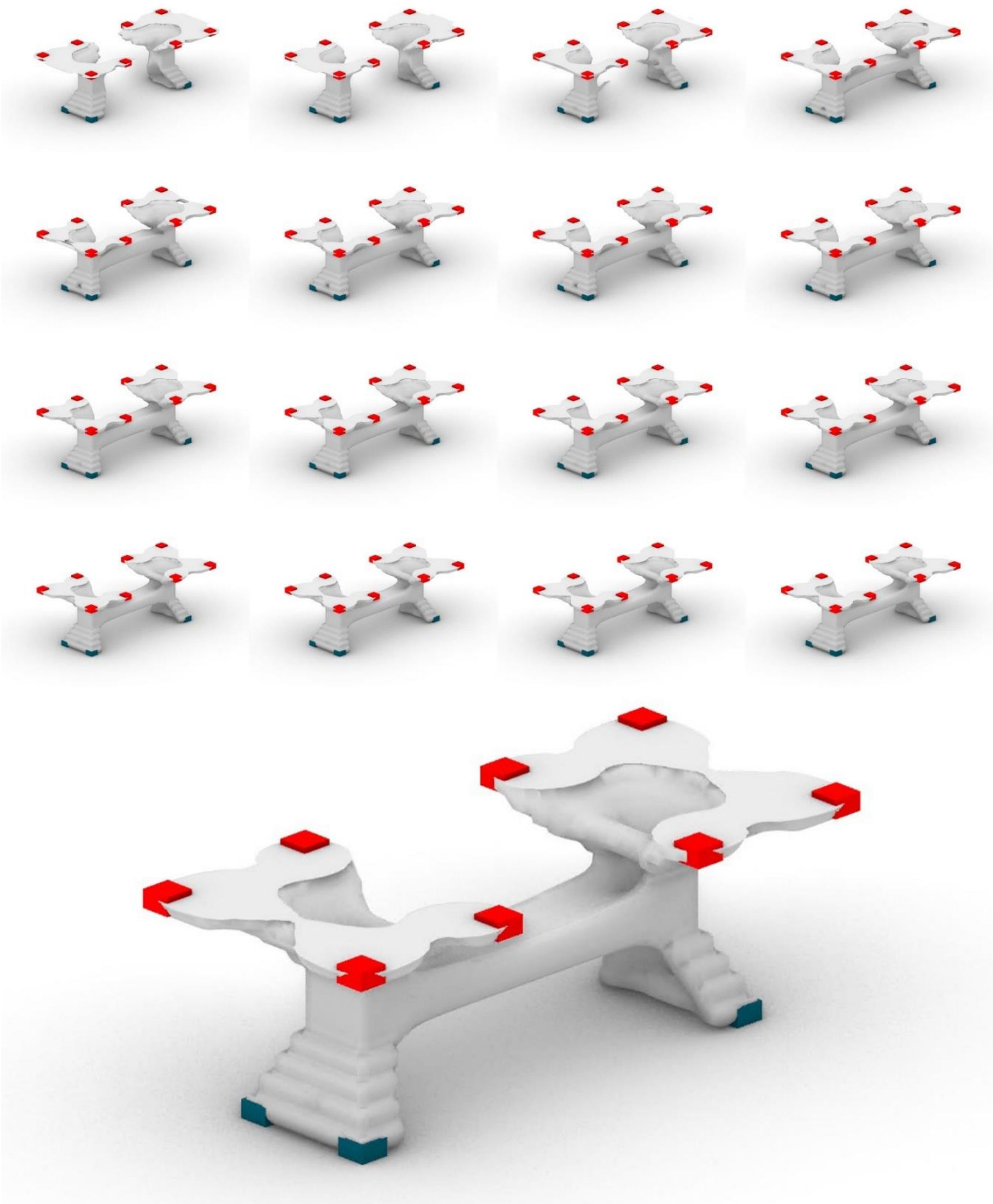

Figure 7. Iterations, (up) The formation procedure of the chosen iteration, (down) Final stage of iteration.

3.5. *Waffle* Structure

Lightweight structure is one of the primary advantages of waffle-structured furniture design. Using a grid-like structure reduces the amount of material required to construct the furniture, resulting in a lighter end product (Figure 8). When approximately 25 cm grid axes are used with the selected material of 1.8 cm thickness used for the study, there is a 92.8% reduction in volume. At this point, the total final volume reduction of the proposed model with a volume fraction of 0.35 entered as a parameter in topology optimization is roughly 97.5 percent.

There is no algorithmic method for determining the waffle structure's axis intervals. Despite the fact that the algorithm determines the cutting drawings, numerous axis numbers and width variations were tested when conceiving the axis layout. Consequently, it was anticipated that a 9 x 4 axis layout would provide sufficient stability when constructing the structure. When creating the waffle structure, the algorithm distributes all axis intervals equally with default preferences. Another advantage of the waffle structure during assembly is part classification and ease of assembly. The algorithm defines the separation of part numbers according to the axes determined in the cutting drawing and the numbering of which part will go where. In addition, thanks to this method's interlocking structure, the structure can be assembled without the use of any tools.

Figure 8. Waffle structure. (top) Volume reduction resulting from optimization; (middle) Installation sequences; (bottom) Final slices.

3.6. Observation via AR in 1/1 Scale

Observation at 1/1 scale using augmented reality technology, the designer virtually observes digital models in real environments (Figure 9). This allows for the demonstration of how the models will appear from various angles and how they will fit into the space. In this project, the developed design was viewed in an augmented reality environment using Arkio software, and the furniture was experienced in its intended location. Hence, the anthropometric data collected exhibited a high level of consistency, with a scale of 1/1 being employed. Furthermore, it was ascertained that there was no intersection between the leg-foot and the structure when looking through AR image. A further advantage of AR for indoor furniture design is the established relationship between scale and space. The three-dimensional relationship that the furniture establishes with the spaces around it, other furniture, and objects can be observed using this method because the design is displayed at its actual scale in the area where it will be placed.

Figure 9. Augmented reality image of the table in the area where it will be placed. (This figure is blurry because it is a photograph of the image in the lens; in augmented reality, the image can only be viewed on the head-mounted display. In addition, the location's distinguishing characteristics are pixelated).

3.7. Computer-Aided Manufacturing and Assembly

In the project, laser cutting 18mm thick MDF was not favored due to its high-energy structure containing a fire hazard, and CNC was deemed suitable for obtaining the slices. CNC cutting has been incorporated into these modules based on the production with 120*80 cm panels taken at the outset of the design. In this instance, it is intended to produce the two main table slices in three pieces each, and then assemble them during the assembly phase (Figure 10). The cutting drawings generated by the algorithm have been manually examined, and joints with acute angles that would pose a challenge for the CNC technique have been rounded. In addition, the waffle structure's required spacing has been increased from 18 mm to 18.5 mm. Thus, excessive friction force was avoided during assembly, thereby locking the system.

Figure 10. Image of the finished product

4. Conclusion

The integration of STO with waffle structure techniques in furniture design has opened new avenues in architectural design and digital culture. The innovative use of anthropometric data, parametric design, and augmented reality has not only enhanced the efficiency of the design process but also allowed for a more personalized approach. The ability to visualize designs in real space through augmented reality provides a tangible connection between the virtual and physical worlds, fostering a more immersive design experience.

While the study has achieved significant success in optimizing design, certain challenges were identified, such as the imbalance in weight distribution due to the lightweight structure, which might lead to instability. These challenges must be addressed in future research to ensure the practical applicability of the methods used.

The Opti-Waffle model developed in this study paves the way for mass customization in furniture design. It demonstrates how parametric design and computer-aided manufacturing can be employed to create unique pieces tailored to specific architectural spaces. This approach not only minimizes waste but also contributes to the creation of lightweight and efficient structures.

Furthermore, the study's methodology, which combines various fields such as machine learning, human-computer interaction, and augmented reality, reflects the growing trend of interdisciplinary collaboration in design.

This study has provided a comprehensive exploration of the potential for integrating STO with waffle structure techniques in architectural design, particularly with regard to the design of furniture. The research has demonstrated how cutting-edge technologies can revolutionize the design process while maintaining cost efficiency. This was accomplished through an approach that was both systematic and interdisciplinary.

The innovative use of anthropometric data to create personalized designs represents a significant advancement in the field. By tailoring designs to individual needs, the study has shown how technology can enhance both the functionality and aesthetics of architectural pieces. The application of waffle structure techniques for sustainability is another standout contribution, reducing material usage by 92.8% and contributing to global sustainability goals.

The utilization of augmented reality for real-space visualization has bridged the gap between virtual designs and physical reality, allowing designers to interact with their creations in a more tangible way. This integration of technology and design has broad implications for the future of architectural education and practice.

However, the study also highlights the need for further investigation into the challenges identified, particularly concerning stability and weight distribution. These challenges present opportunities for future research and development, paving the way for more robust and practical solutions.

Opti-Waffle model developed here offers a pathway towards mass customization and sustainable design practices. It stands as a testament to the transformative power of technology in design, underscoring the endless possibilities that lie at the intersection of creativity, innovation, and interdisciplinary collaboration.

In conclusion, the findings of this research contribute significantly to the broader discourse on architecture design, parametric design, and digital culture. They provide valuable insights and directions for future exploration in these domains, highlighting the importance of continuous innovation and collaboration. The study serves as a source of inspiration for future researchers and practitioners, motivating them to expand the limits of architectural design and to explore novel approaches in the fusion of technology and creativity.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	E.Y.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

There is no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans. The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to.

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