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Improving Interior Design: Topology Optimization and Large--Scale 3D Printing Plastic

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Abstract

The pervasive use of plastics, despite their economic benefits in recycling and reuse due to their low cost and abundance, has contributed significantly to global environmental issues, including pollution and global warming. Notably, polymer production continues to rise, paralleling increasing environmental impacts. This paper shifts focus from these broader environmental concerns to explore how topology optimization and advanced 3D printing technologies are transforming interior design. Specifically, it examines the integration of topology optimization a technique traditionally used in engineering to distribute materials efficiently within a design space to enhance both the sustainability and creativity of large-scale 3D printing applications in interior design. By optimizing material usage and minimizing waste, these technologies not only address some environmental concerns associated with plastics but also revolutionize how designers conceive and implement interior spaces. The paper highlights case studies where these integrated technologies have enabled unprecedented levels of creativity and efficiency, redefining the aesthetics and functionality of interior environments.

Keywords: Topology Optimization, Large Scale 3D printing, Recycled plastic

1. Introduction

Over the last few years, the increasing awareness of plastic pollution has driven researchers, architects, and designers to explore better uses for recycled plastics in their projects. The advent of robotics and 3D printing technologies, when combined with topology optimization, has opened new doors for developing innovative construction solutions. Since its emergence in the mid--1980s, additive manufacturing, or 3D printing, has experienced significant growth and has been adopted across various industries. In the construction industry, this technology enables architects and designers to enhance their designs, significantly reducing construction time and transcending the limitations of traditional manufacturing methods. 3D printing facilitates the creation of complex structures and unusual angles (Skoratko & Katzer, 2021). Additionally, its automated nature significantly reduces the likelihood of human error, injuries, or fatalities, thereby enhancing the safety of the construction process (Tay et al., 2017).

On the other hand, topology optimization is commonly used in industrial product design, such as in aerospace and automotive sectors, where the efficiency of mechanical parts and material usage is crucial (Bialkowski, 2016), This method is also well-established in the civil engineering field. For instance, Guest and Moen have discussed the topology optimization of reinforced concrete members, developing solutions that feature curved compressive struts more consistent with elastic stress trajectories than traditional strut--and-tie models derived by hand (Guest & Moen, 2010).

In recent years, both 3D printing and topology optimization have garnered attention from architects and designers for their ability to create elegant, organic forms by determining voids in continuum structures. However, according to the literature review we conducted, no existing research discussing the implementation of topology optimization at the design stage of 3D-printed interior designs was found. Therefore, this study focuses on utilizing the results of topology optimization analysis in combination with design of 3D-printed wall panels.

2. Understanding Topology Optimization

Topology optimization is a mathematical method that optimally distributes material within a defined domain. It operates under constraints to minimize a predefined cost function, effectively functioning as a performance-based design tool. This method aims to find the most efficient structural form, meaning that the generated configuration corresponds to an optimized material layout under a set of defined conditions for a given volume (Xie, 2022). In architectural design, two commonly used techniques of topology optimization are the evolutionary structural optimization (ESO) method and the bidirectional evolutionary structural optimization (BESO) method (Xie, 2022).

The ESO method, introduced in 1993 by Y.M. Xie and G.P. Steven, is based on the simple concept of gradually removing inefficient material from a structure during its design. This method employs a finite element (FE) method to construct the design domain, applying external loads and support conditions to the element model. As the optimization progresses, the structure evolves towards its optimal shape by removing low-stressed elements based on calculations of Von Mises stress or strain energy density. However, since inefficient elements are completely eliminated, there is no residual information about their effects on the objective function in later stages of the optimization process (Shobeiri, 2016).

Developed by Querin et al., the BESO method combines additive evolutionary structure optimization (AESO) with ESO. This approach not only removes inefficient elements but also adds efficient ones simultaneously, improving upon the original ESO method. The BESO method offers several advantages over its predecessor, including greater robustness, computational efficiency, and versatility in optimizing a variety of structures (Xiangfeng et al., 2011; Yan Li et al., 2013).

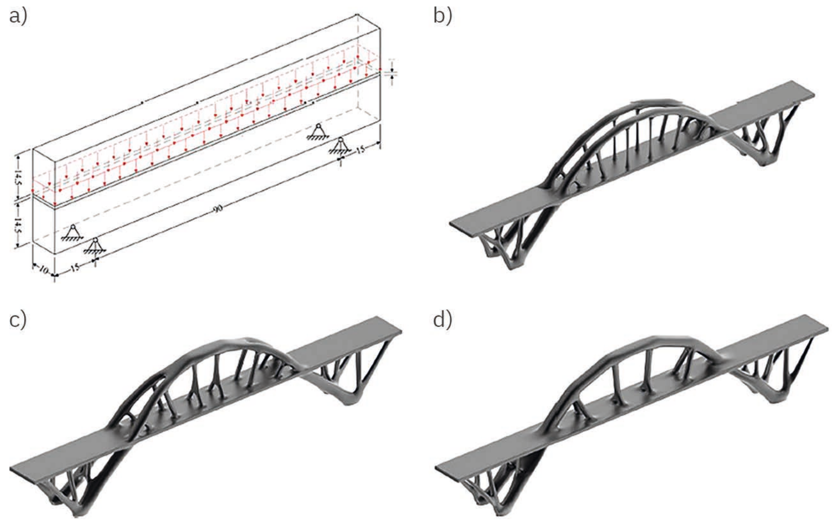

Fig. 1. Multiple designs of a bridge structure: a) load and support conditions; b) initial optimized design; c) and d) subsequent designs generated by penalizing all precedent designs (Yang et al., 2019)

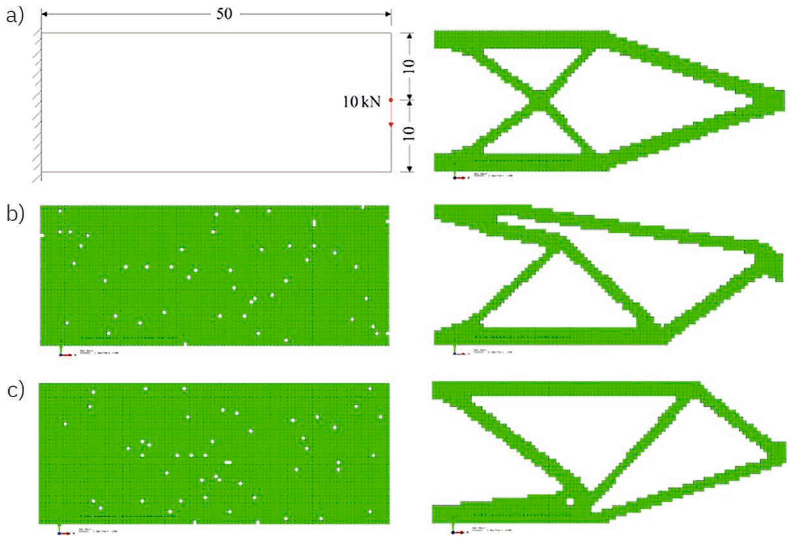

Fig. 2. Multiple designs of a cantilever beam: a) conventional optimized design; b) and c) alternative designs generated by setting random voids in the initial model (Xie et al., 2019)

3. Large-scale 3D printing

In their research, Al Jassmi et al. emphasize the interdisciplinary nature of large-scale 3D printing, highlighting the need for a diverse knowledge base spanning various fields such as structural engineering, materials science, mechatronics, software engineering, artificial intelligence, and architectural engineering (Al Jassmi et al., 2018). The fundamental principles of 3D printing entail layer--by-layer fabrication from digital files, employing technologies such as material extrusion, vat photopolymerization, material jetting, binder jetting, and powder bed fusion. Over time, large-scale 3D printing has evolved and improved to address challenges encountered across different sectors. Presently, various types of 3D printing technologies are prevalent, including:

- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- Fused Deposition Modeling (FDM)

3.1. Stereolithography (SLA)

SLA is one of the most widely used vat photopolymerization technologies. It creates objects by selectively curing a polymer resin, layer by layer, using an ultraviolet (UV) laser beam. The materials used in SLA are photosensitive thermoset polymers that come in a liquid form. Materials use for SLA come in form of liquid resins, which can be chosen based on the end use of the part–for example, thermal resistance properties, a smooth surface finish or abrasion resistance (Protolabs Network, 2024b.000Z).

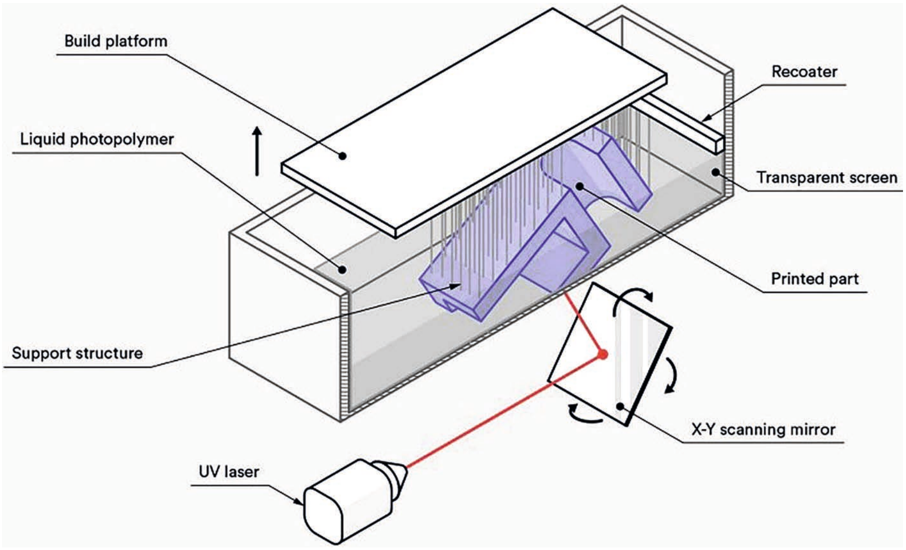

Fig. 3. Schematic of SLA printer (Protolabs Network, 2024b.000Z)

3.2. Selective Laser Sintering (SLS)

Selective laser sintering is an additive manufacturing (AM) technology that uses a high-power laser to sinter small particles of polymer powder into a solid structure based on a 3D model. SLS 3D printing has been a popular choice for engineers and manufacturers for decades. The most common material for selective laser sintering is nylon, a highly capable engineering thermoplastic for both functional prototyping and end-use production.

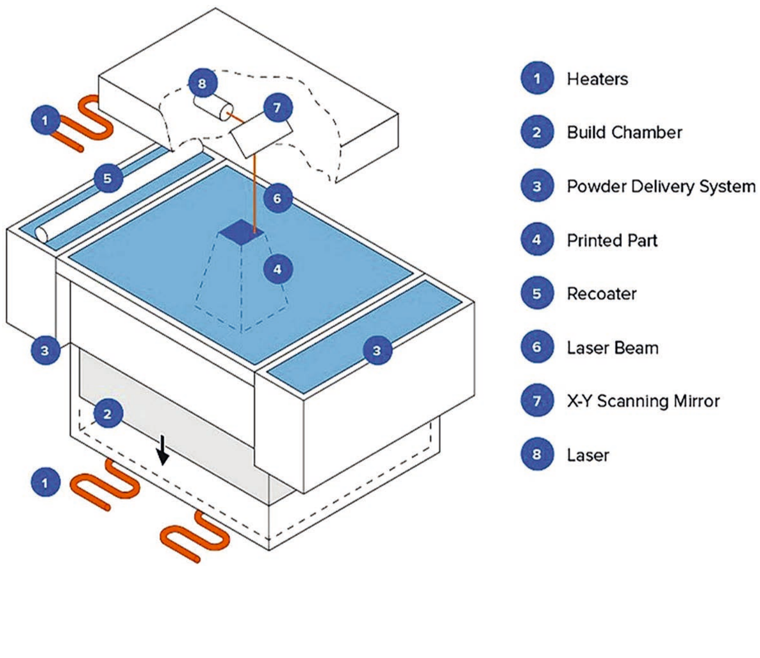

Fig. 4. Schematic of the selective laser sintering process. SLS 3D printing uses a high-power laser to sinter small particles of polymer powder into a solid structure based on a 3D model (Formlabs, 2024.000Z)

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3.3. Fused Deposition Modeling (FDM)

For PROTOLABS NETWORK, Fused deposition modeling (FDM) 3D printing, also known as fused filament fabrication (FFF), is an additive manufacturing (AM) process within the realm of material extrusion. FDM builds parts layer by layer by selectively depositing melted material in a predetermined path. It uses thermoplastic polymers that come in filaments to form the final physical objects (Protolabs Network, 2024a.000Z). In this research, this printing technique will be used not only because it is one of the most commonly used in the construction industry, but also because previous research provides extensive information about the mechanical properties of 3D-printed elements made with this technique, which is necessary for topology optimization.

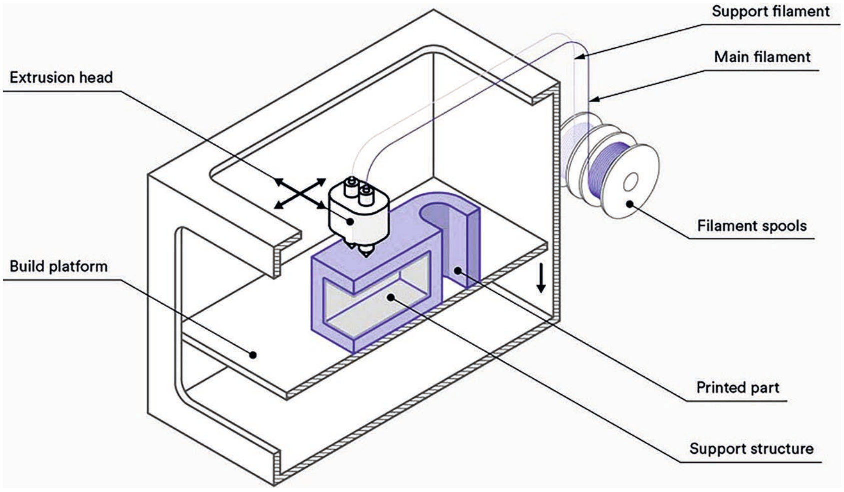

Fig. 5. Schematic of a typical FDM printer (Protolabs Network, 2024a.000Z)

3.4. 3D printing filament from recycled plastics

Recycled plastic gain momentum in 3D printing filament through a multistep process: waste plastic collection, sorting, cleaning, shredding, and extrusion. The beginning consists of waste plastic collection, the most common being bottles (PET) and packaging material (PLA and ABS), sorted to separate contaminants and different types of plastic. After it has been cleaned, the plastic is shredded into small flakes, which are much easier to melt down in further steps. These flakes are then fed into an extruder-a machine that heats and melts the flakes-forcing the molten plastic through a nozzle in such a way that one gets a filament, a sort of continuous strand. This filament is cooled, wound onto spools, and checked for consistent diameter to ensure high-quality printing performance. Filtration systems are mostly involved in the process of extrusion for taking out impurities, which help improve filament strength and print quality (Mikula et al., 2021; Nikam et al., 2023). Recycled filaments offer a sustainable option for 3D printing, diverting plastic from landfills and conserving resources.

4. Method

The primary aim of this research is to assess the benefits of integrating topology optimization into the design phase of wall panels. The study will focus on wall panels measuring 250 cm in height and 375 cm in length. The main parts of this study will include:

- Defining the type of element
- Topology optimization
- Parametric design base on result of the topology optimization

In the present work, we are going to study two kinds and variants of infill, but it is interesting to point out that the pattern adopted for the arrangement of the panels is not the only comparison parameter. Indeed, the infill percentage, intended as the proportion of solid material within the internal structure of the part, represents a very important factor since the mechanical properties of a 3D printed part, such as strength, stiffness and durability, are highly dependent on it (Qamar Tanveer et al., 2022). With increased infill percentage, strength and rigidity are much higher because the material is denser within the part and will give greater resistance to deformation under load. Low infill percentages produce lighter but weaker parts that easily can fail under mechanical stresses. These mechanical properties mentioned above are the indispensable consideration during the topology optimization process, which balances material usage and structural performance, optimizing the part's geometry to deliver the required strength with minimum weight and material cost (Iqbal, 2021). By tuning the infill density, we are in a position to reinforce selected areas without compromising the total mass. Accordingly, this understanding of the interplay between infill percentage and mechanical performance allows 3D-printed components to be tailored with a great deal of precision, which enables optimization in both topological and mechanical performances.

4.1. Defining the type of element

In construction sector we have two main type of element which are nonbearing element and loadbearing element (Adam & Furtmüller, 2008). In this study, we are designing a non-load-bearing element intended for attachment to a wall as a decorative panel. To ensure the rigidity of the element, we plan to secure the printed wall panel to the wall using screws. Fixing holes will be incorporated into the printed element to facilitate installation. We explored two types and variants of fixing in this study.

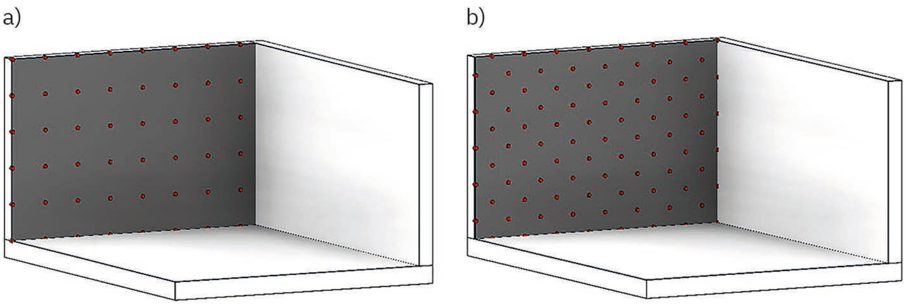

Fig. 6. Fixing variants: a) square as a basic fixing module; b) rhombus as a basic fixing module (own elaboration)

4.2. Topology optimization

Topology optimization, as an engineering tool, is seldom utilized in the architectural design process. This is primarily due to the complexity and time-consuming nature of the process required to achieve results that meet a designer's expectations (Bialkowski, 2016). The analysis involves a sequence of complex mathematical equations, often inaccessible to many architects due to their background.

However, with advancements in research and technology, there are now software solutions with user-friendly options that can be easily utilized by architects and designers. For our study, we utilized Autodesk Fusion 360, one such software, which offers a Topology Optimization workbench, it is one of the latest emerging software and it has Topology Optimization workbench (Shanmugasundar et al., 2021).

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4.2.1. 3D model of the a subpart of the wall panel

The initial step in conducting topology optimization is to model the geometry that you intend to optimize. In our study, we focused on modeling a specific subpart of the entire wall panel. Given that the fixing distance remains consistent, we treated this subpart as a modular component that could be easily replicated.

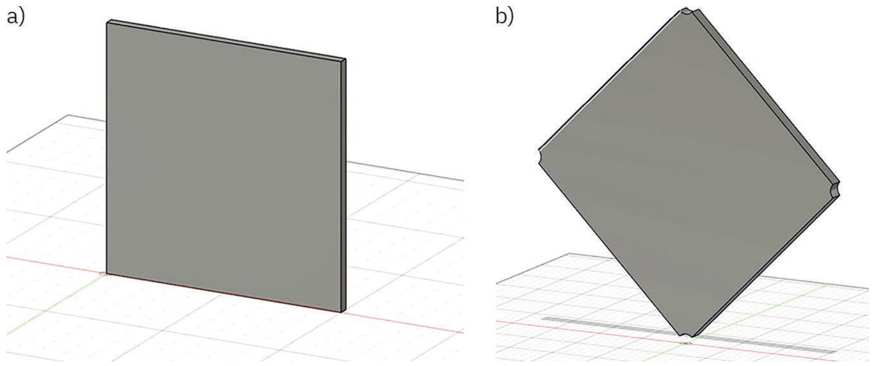

Fig. 7. 3D model of modular panels: a) variant 01; b) variant 02 (own elaboration)

4.2.2. Material properties

The mechanical properties of the components represent another crucial input needed to construct the topology optimization model. Typically, a series of uniaxial tensile tests are conducted in the laboratory on the material, following relevant test standards. Additionally, a cyclic tensile test is often necessary to capture the material's dynamic response, as demonstrated in the study by the authors (Woern et al., 2018).

Table 1. Material properties (PET). (Woern et al., 2018)

Density	1.541E-06 kg/mm^3
Young's Modulus	2.758 GPa
Poisson's Ratio	0.417
Yield strength	54.40 MPa
Ultimate tensile strength	55.10 MPa
Specific heat	2287.00J/(kg C)

4.2.3. Boundary conditions

The type of mounting has been used at this stage to define the boundary conditions, in fact the points where the panels are fixed to the wall have been defined as fixed points in the software and we have defined only gravity as

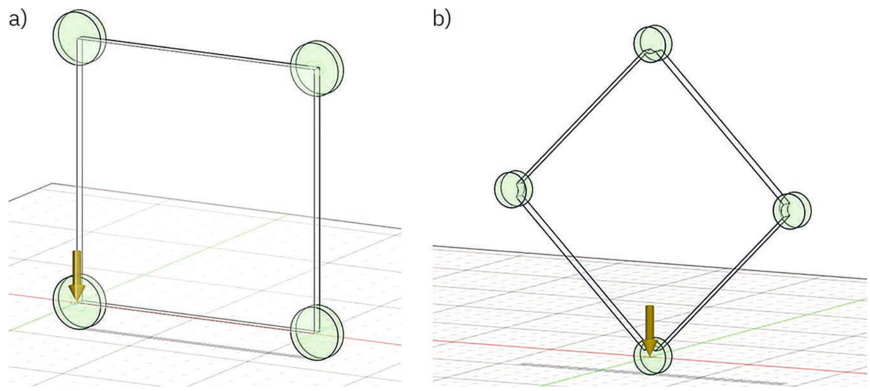

Fig. 8. Boundary conditions of modular panels: a) variant 01; b) variant 02 (own elaboration)

the load on our panels since these panels will not support any load apart from its load.

4.2.4. Mesh properties

The finite element method works by breaking down a real object into a large number (1,000s to 100,000s) of elements, such as little tetrahedra or cubes, called a mesh. Autodesk Fusion provides automated mesh generation along with both global and local settings for the mesh size, mesh quality, element order, and other options.

- Mesh settings apply to all components.
- Local mesh controls apply to selected entities.
- Each simulation study has its own mesh settings.

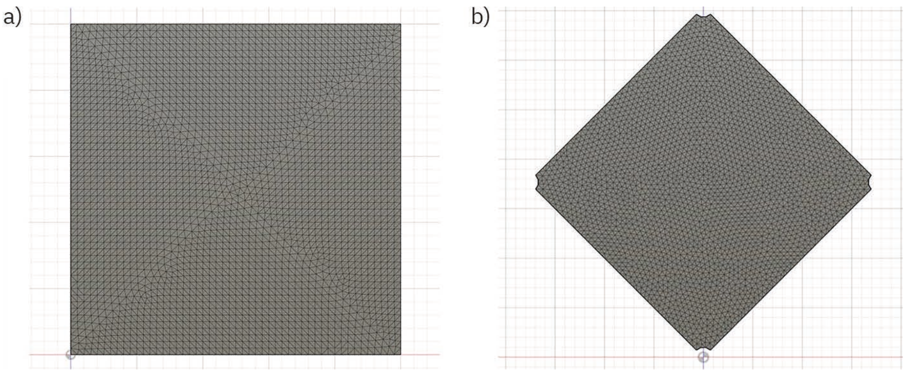

Fig. 9. Mesh view on modular parts:
a) variant 01; b) variant 02 (own elaboration)

4.2.5. Results of the topology optimization

The last step before starting the analysis was to define percentage of the material you want to keep. For this analysis, 60% of the initial material was supposed to be safe. The result show in this section in the result.

The Evolutionary Structural Optimization (ESO) method was used to conduct this analysis. As shown in the legend on Fig. 10 and Fig. 11, the blue areas represent the least useful parts of the basic domain, while the red areas indicate regions with the highest force distribution, which are essential for the panel's stability.

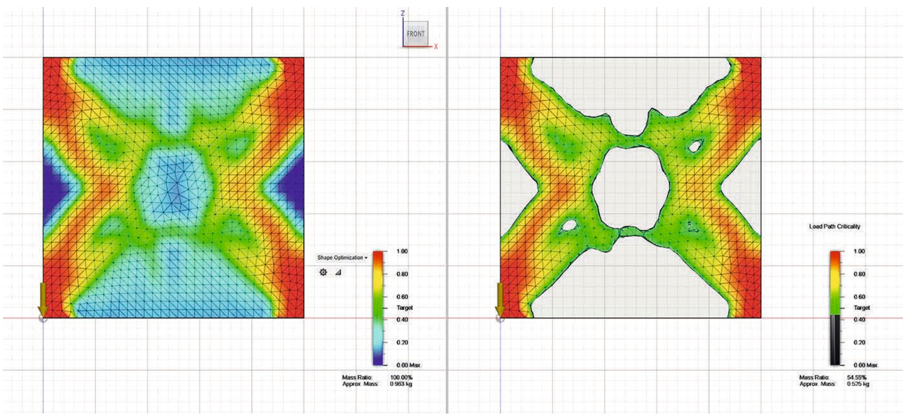

Fig. 10. Result of topology optimization variant 01 (own elaboration)

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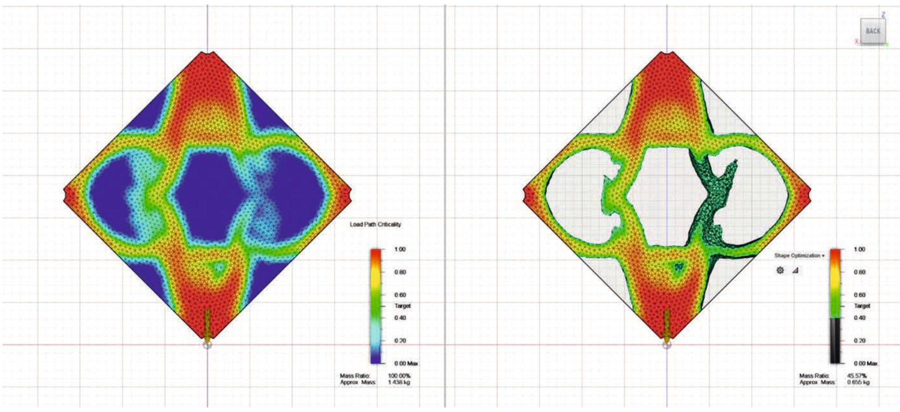

Fig. 11. Result of topology optimization variant 02 (own elaboration)

4.3. Parametric Design

The aim of this phase was to utilize the outcome of the topology optimization as a foundation for understanding the structural behavior of each subpart of the wall panel, and to utilize the resultant shape as the basis for parametric design.

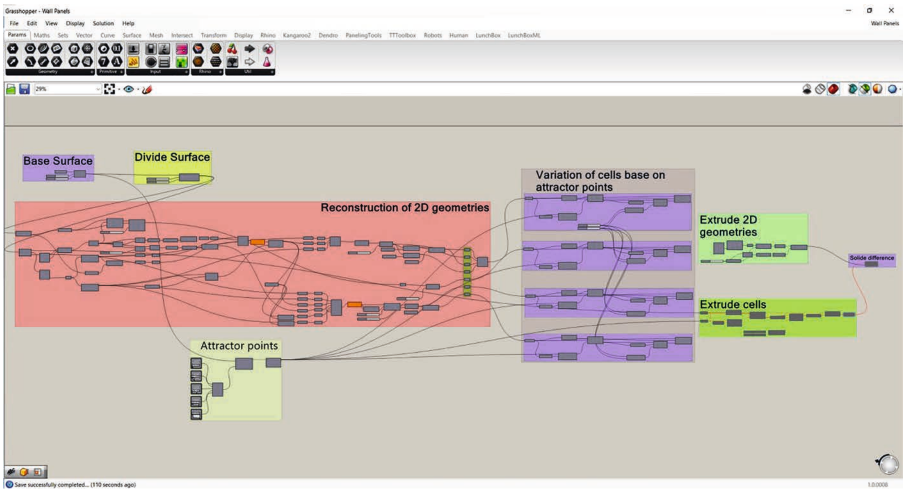

Fig. 12. Parametric design Process (own elaboration)

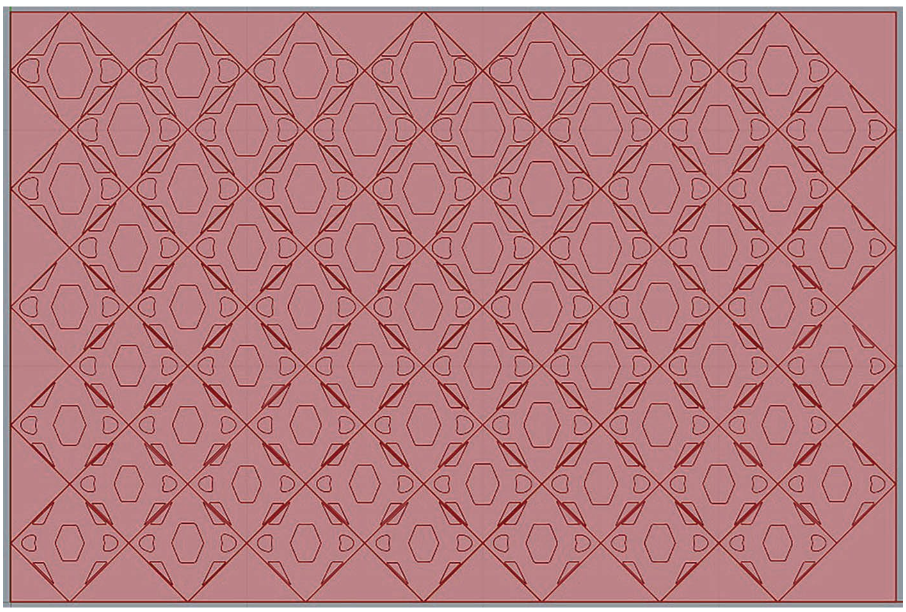

Fig. 13. 2D result of the design process (own elaboration)

At this stage of the research, the result shape of the variant 02 was selected to conduct the research. We used Rhinoceros 8 and its plugin Grasshopper to first of reconstruct the 2D geometry of the result shape and then, by playing with the attractors points, we reduced the amount of initial material base on the ration we set during the topology optimization.

5. 3D visualization of the result

The images below are 3D visualizations of the study's results. The Lumion extension was used to export the 3D model to Lumion, and the renderings were produced using Lumion Student 2023.

Fig. 14. 3D visualization of the result (own elaboration)

The panel designed in this research will mainly be used as a decorative panel, where by playing with the diffusion of light through the 3D printed panels, the ambient luminance of the room can be influenced (as shown in figure above). Additionally, the panel can be designed to serve as an interactive component within the space, influencing the boundary condition of the element as indicated in sections 4.1 and 4.2 of this study. In this study, we sought to minimize the interaction between panels and the room, as this would influence the amount of plastic used for each panel. This is because the resistance of the panel is highly linked with the density of the 3D printing element.

The mean weight of the designed panels is 120 g, which is approximately equivalent to 38.77 m of 3D printing filament with a string diameter of 1.75 mm. In this context, the resulting wall panel can be used not only for decorative purposes but also as insulation and to affect the interior lighting of the room by playing with the diffusion of light through the panels. Additionally, Printed plastic objects, when properly made and used, are normally safe for home use. Most 3D printers would use PLA (polylactic acid), a bio plastic, sourced from renewable resources like corn starch or PET (polyethylene terephthalate) and its modified form PETG (polyethylene terephthalate glycol-modified) for its durability, ease of use, and safety (Kim et al.). PLA and PET is generally thought to be safe for use in the home due to its not requiring high temperatures during printing, which limits the release of possibly harmful particles into the air. In this regard, a study by Zontek et al. (2017) stated that PLA and PET emitted significantly low levels of particulate matter and VOCs compared to ABS while 3D printing, hence supporting its safety in indoor applications. Again, maintaining good ventilation and the use of quality filaments with a safety standard further ensure safety for printed plastic objects in home settings.

6. Further work

3D prototypes will be 3D printed for the purpose of physical tests. Based on the results of these tests, any necessary adjustments will be made before proceeding to print a full-scale version of the object. This will allow us to effectively demonstrate the advantages of using this process in the design of interior elements.

Following this stage, our aim is to extend the use of 3D printed plastic elements to the exterior of buildings. However, it is important to note that, according to the author's research, plastic may experience deterioration in mechanical and physical properties when exposed to outdoor conditions for extended periods of time

7. Conclusion

The integration of recycled plastics into design and architecture stands as a pivotal asset in combating environmental pollution stemming from plastic waste. Yet, the incorporation of topological optimization emerges as an indispensable process in the design phase. It not only facilitates morphological research but also elucidates the structural operating principles of our designs, thereby rationalizing material usage. Moreover, the fusion of topological optimization with the vast possibilities afforded by large-scale 3D printing of plastics in interior design projects promises not only a reduction in plastic waste but also the proposition of rational and aesthetically pleasing solutions.

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