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A NOVEL FRAMEWORK FOR THE APPLICATION OF TOPOLOGY OPTIMIZATION IN LIGHTWEIGHT STRUCTURES

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Abstract
Introduction: Topology optimization has been widely used in the fields of mechanical and structural engineering. In the field of architecture, especially in the context of lightweight structures, a strong understanding of programming is essential for meaningful involvement. The **purpose of the study** was to establish a fundamental framework that facilitates the seamless implementation of topology optimization in the design of lightweight structures by architects. **Methods**: This work employed a deductive approach to analyze six case studies that involve the application of topology optimization in various lightweight constructions. The analysis was conducted based on a predefined set of criteria. Additionally, the deductive technique was used to establish a framework for implementing topology optimization in the design of lightweight structures. Finally, the framework was used to create an optimized lightweight structure (a pentagonal Roman vault). **Findings:** An analysis of all case studies was conducted using two distinct processes: the form-finding process and the fabrication process. This inquiry aimed to determine the procedural framework involved in the design and fabrication process of each case study. The underlying framework was derived through an analytical comparison of these six case studies. This framework enables the production of an optimized lightweight structure. **Novelty:** This study presents significant findings on topology optimization and its use in lightweight structures, offering essential insights for architects seeking to create aesthetically pleasing and distinctive architectural forms that prioritize high stiffness and low mass.

Keywords: lightweight structures, topology optimization, additive manufacturing.

Introduction

Topology optimization is a mathematical methodology that aims to optimize structures by taking into account several design factors, including applied loads, supports, available design domain, materials, and cost considerations. Using this approach in the initial stages of the design process allows for the creation of designs that have minimal mass and optimal stiffness (Ma et al., 2021; Tedeschi, 2014). The generation of outputs from topology optimization algorithms might pose challenges, necessitating subsequent refinement to ensure the manufacturability of the final result. In certain circumstances, it is possible to directly manufacture the results of topology optimization through the use of additive manufacturing techniques (Woo, 2020). Topology optimization is a form of generative design that leverages the computer's ability to perform rapid computations to generate shapes (Tedeschi, 2014). Topology optimization has drawn the attention of many architects among the different generative design tools due to its capacity to produce attractive organic forms by identifying voids in continuum structures (Liu et al., 2019). More importantly, topology optimization is a performance-based design method that seeks the most efficient structural form, which means that the resulting configuration corresponds to an optimized material arrangement (Javadi Moghaddam et al., 2023; Xie, 2022). Topology optimization plays a significant role in the field of architecture as it helps determine the optimal placement and dimensions of architectural components. Designers can optimize mechanical components or parts using this technique, which often involves reducing material usage. Topology optimization offers cost-saving solutions thanks to lightweight structures and efficient design procedures. In addition, creating optimal structures that exhibit such characteristics as lightweightness, durability, and cost-effectiveness is beneficial (Liu et al., 2022; Yıldırım, 2022).

Topology optimization solves multiple problems. It has numerous advantages: creating cost-effective and lightweight solutions by reducing unnecessary weight and raw material usage. Design constraints and performance targets are considered early in the design process, resulting in a quicker final design through topology optimization. Topology optimization is increasingly being adopted by various industrial sectors in response to the growing demand for eco-friendly options, aiming to reduce unnecessary material waste for sustainable perfection (Tedeschi, 2014).

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There are certain drawbacks associated with topology optimization that should be considered:

a. The use of intricate patterns may have both benefits and drawbacks.

b. Early investments in software, training, and computational resources may be necessary.

c. Manufacturing incurs significant costs due to the expensive nature of some manufacturing methods required for topology-optimized designs.

d. Designers may need to establish manual constraints in order to ensure the feasibility of manufacturing and meet other requirements.

e. Training is a necessary component for the appropriate utilization of topology optimization technologies.

f. Limited use of primary resources: The use of specific raw materials in topology-optimized designs may be subject to constraints or limitations, depending on input parameters.

g. The output quality depends on the accuracy of the input parameters provided by the designer (Sigmund and Maute, 2013).

Additionally, these data-driven topology optimization methods enable the calculation of resistances, damage properties, and structural connections of real materials. Furthermore, they facilitate the exploration of unconventional structural systems and the identification of novel and efficient structural solutions suitable for specific circumstances. The approaches discussed in this study include solid isotropic material with penalization (SIMP), evolutionary structural optimization (ESO), bi-directional evolutionary structural optimization (BESO), and level-set method (LSM) (Bao et al., 2020; Woo, 2020).

Methodology

The methodology employed in this study is based on examining six individual case studies that have implemented a specific topology optimization technique. The selection of these case studies was primarily based on the criteria established by the authors. The mentioned criteria include the following aspects: first, the structure must have a lightweight composition; second, the structure must undergo digital manufacturing using various techniques; third, it must have been designed using one of the topology optimization approaches; and finally, it must have been constructed within the past decade. The selected case studies, in sequential order, are Pavilion X-Form 1.0 (Bao et al., 2019, 2020), Pavilion X-Form 2.0 (Bao et al., 2022), VOLU Dining Pavilion (Bhooshan, 2017; Louth et al., 2017), Tailored Biocomposite Canopy (Dahy et al., 2020; Martins et al., 2020; Rihaczek et al., 2020), Trabeculae Pavilion (Naboni et al., 2019), and Cloud Pavilion 2.0 (Chen et al., 2019) as shown in Fig. 1.

There are four case studies that exhibit continuum structures, while two case studies demonstrate discrete structures. The pavilions known as X-Form 1.0 and X-Form 2.0, both created by the same team, along with the VOLU Pavilion and the Tailored Biocomposite Canopy, might be seen as examples of continuum structures. Furthermore, both the Trabeculae Pavilion and the Cloud Pavilion 2.0 can be classified as discrete structures. An analysis of all case studies was conducted using two distinct processes: the form-finding process and the production and assembly process. Next, we shall proceed to deduce the sequence of steps involved in the process of designing and constructing each case study, as outlined in Table 2. A comparative analysis was conducted, as depicted in Table 1, to examine the six case studies in relation to various aspects. These aspects include the structural type (with the exception of the Tailored Biocomposite Canopy, all case studies feature a shell structure), whether the structure is considered as continuum or discrete, the approach employed for form finding, the specific topology optimization method utilized (ranging from SIMP to BESO), the materials used, the software utilized, and the fabrication technique employed. The analysis process is a crucial component in establishing the framework for implementing topology optimization in a lightweight structure.

Discussion

To effectively implement topology optimization in the design of lightweight structures, it is important to have the basic geometric configuration of the structure before starting the topology optimization procedure. Based on the examination of prior case studies, it has been inferred that there are two primary procedures for implementing topology optimization in the context of lightweight structures. These procedures encompass the form-finding

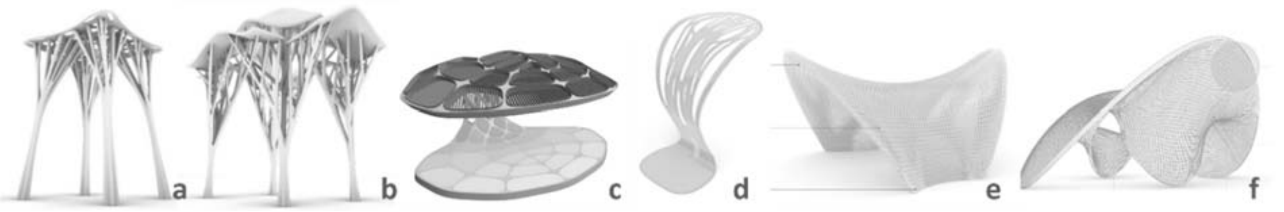
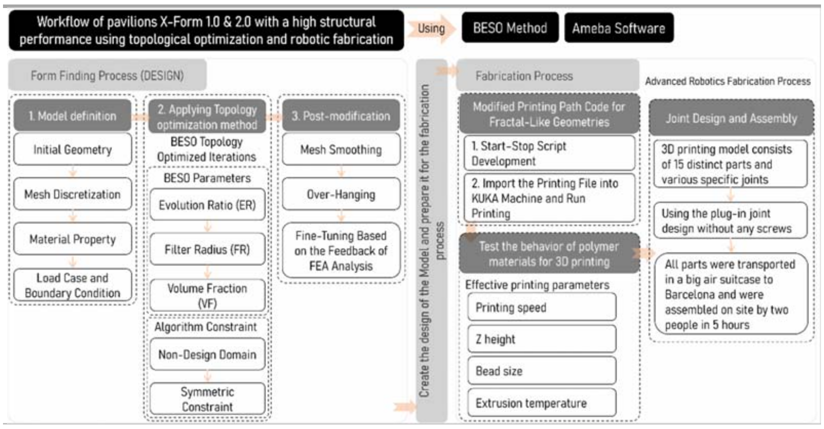


Fig. 1. Six case studies used in the analysis: a — Pavilion X-Form 1.0; b — Pavilion X-Form 2.0; c — VOLU Dining Pavilion; d — Tailored Biocomposite Canopy; e — Trabeculae Pavilion, f. Cloud Pavilion 2.0

Table 1. **Comparative analysis of the six case studies applying topology optimization in lightweight structures**

Project name	Type of structure	Form finding	TO method	Materials	Software	Fabrication technique
X-Form 1.0 & 2.0 Pavilions	Continuum structure	Tree-like structure form	BESO method	3D printing of fireproof polymeric materials / PETG materials	Ameba in Rhino-Grasshopper	Large-scale robotic 3D printing
VOLU Dining Pavilion	Continuum structure	Curvy clamshell-like structure	SIMP method	Stainless steel, aluminum, and wood	Altair HyperWorks and Altair OptiStruct	CNC laser cutting
Tailored Bio-composite Canopy	Continuum structure	single-curved canopy with no connections	SIMP method	Natural fiber materials / continuous flax fibers	Galapagos & Millipede in Rhino-Grasshopper	TFP (tailored fiber placement) method
Trabeculae Pavilion	Discrete structure	the materialization logic of trabeculae, the interior cells that form the bone microstructure	SIMP method	High-resistance biopolymer	Millipede, Karamba in Rhino-Grasshopper, and Ansys	FDM (fused deposition modeling)
Cloud Pavilion 2.0	Discrete structure	generated using a structural performance-based topological optimization algorithm	SIMP method	3D printing material	Millipede in Rhino-Grasshopper	Robotic 3D printing

Table 2. **Comparative analysis of the workflow in the six case studies**

<table>
<tr><th>Project name</th><th>Workflow</th></tr>
<tr><td>X-Form 1.0 & 2.0 Pavilions</td><td>


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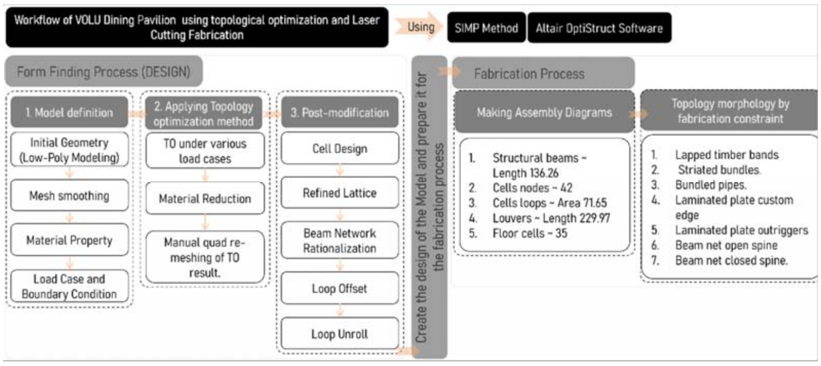
<tr><td>VOLU Dining Pavilion</td><td>


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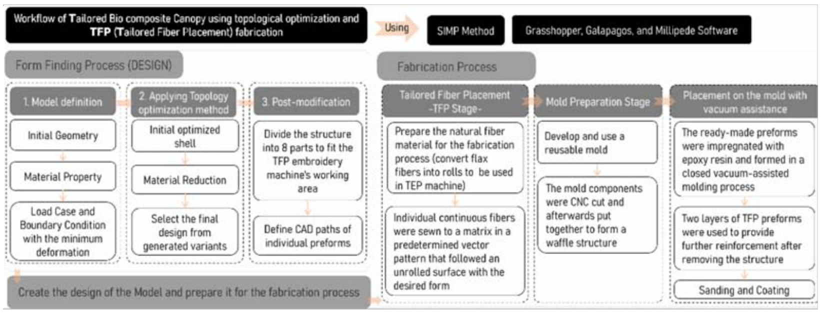
<tr><td>Tailored Bio-composite Canopy</td><td>


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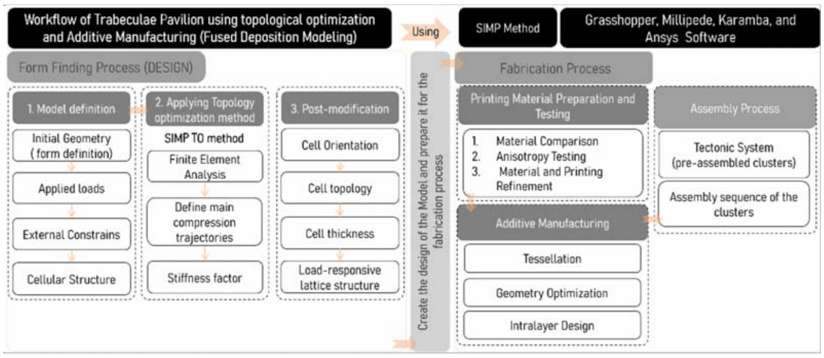
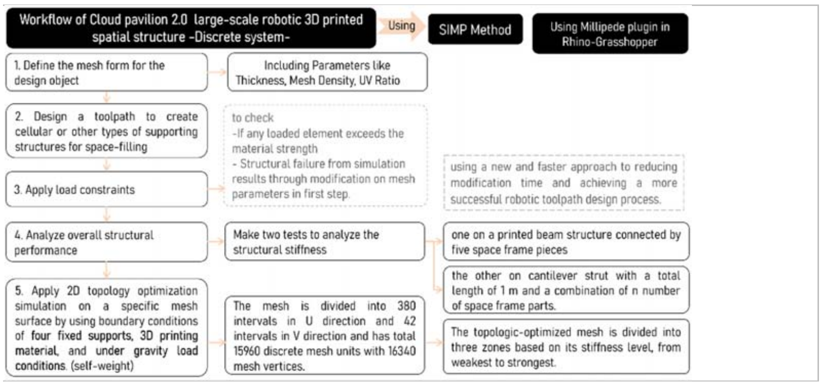
Table 2 (ending)

Project name	Workflow
Trabeculae Pavilion	
Cloud Pavilion 2.0	 1. Define the mesh form for the design object Including Parameters like Thickness, Mesh Density, UV Ratio 2. Design a toolpath to create cellular or other types of supporting structures for space-filling to check -If any loaded element exceeds the material strength - Structural failure from simulation results through modification on mesh parameters in first step. using a new and faster approach to reducing modification time and achieving a more successful robotic toolpath design process. 3. Apply load constraints 4. Analyze overall structural performance Make two tests to analyze the structural stiffness one on a printed beam structure connected by five space frame pieces the other on cantilever strut with a total length of 1 m and a combination of n number of space frame parts. 5. Apply 2D topology optimization simulation on a specific mesh surface by using boundary conditions of four fixed supports, 3D printing material, and under gravity load conditions. (self-weight) The mesh is divided into 380 intervals in U direction and 42 intervals in V direction and has total 15960 discrete mesh units with 16340 mesh vertices. The topologic-optimized mesh is divided into three zones based on its stiffness level, from weakest to strongest.

process and the fabrication process. The form-finding process refers to the analytical and optimization procedures involved in the design of a structure. The process has three distinct stages: model definition, application of the topology optimization method, and post-modification. The fabrication process has four distinct phases, including the selection of an appropriate digital manufacturing technique, the preparation and testing of materials, the design of fabrication and joints, and the final assembly phase. as can be seen in Fig. 2.

Form-finding process

Model definition

The initial stage, referred to as “Model Definition”, includes a series of four sequential processes. The first step involves establishing the boundary domain for the structure in question, to which the subsequent topology optimization will be applied. The process of mesh discretization involves dividing the mesh into smaller sections to accurately determine the positions of loads. Additionally, it is necessary to specify the material properties by providing the value

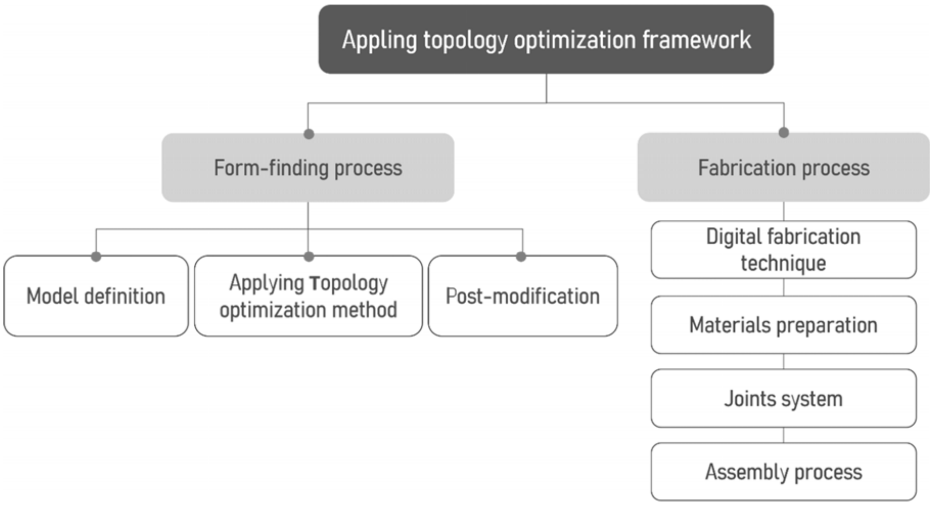


Fig. 2. Primary process of applying topology optimization to lightweight structures (created by the authors)

of Young's modulus in gigapascals (GPa) and the corresponding Poisson's ratio. In conclusion, the applied loads include external loads, the structure's self-weight, the positioning of supports, and structural constraints such as specified openings, doors, or windows, as depicted in Fig. 3.

The authors have developed and presented a case study in order to adhere to and implement the established framework. The chosen design for the vault is a pentagonal Roman vault, which is inspired by the Mortuary Chapel for the Soriano Manzanet family (architizer.com, 2023). The vault has dimensions of 2.4 m for each side and a height of 2.8 m. It features a total of five openings. Later, the surface was discretized into smaller components to accurately determine the locations of the applied loads. Young's modulus and Poisson's ratio for the PLA material used in 3D printing were determined to be 2.7 GPa and 0.3, respectively. The placements of loads and supports were specified as depicted in Fig. 4.

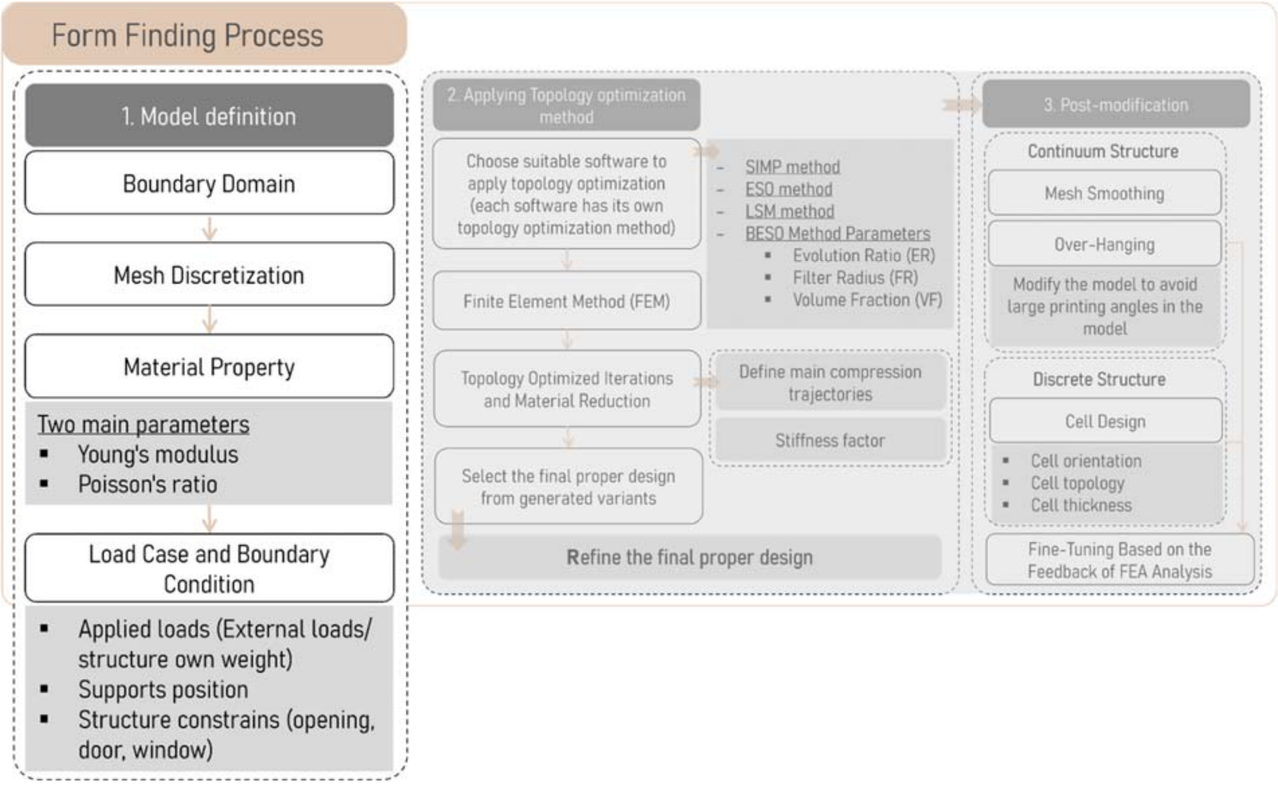


Fig. 3. Workflow of the form-finding process, model definition phase (created by the authors)

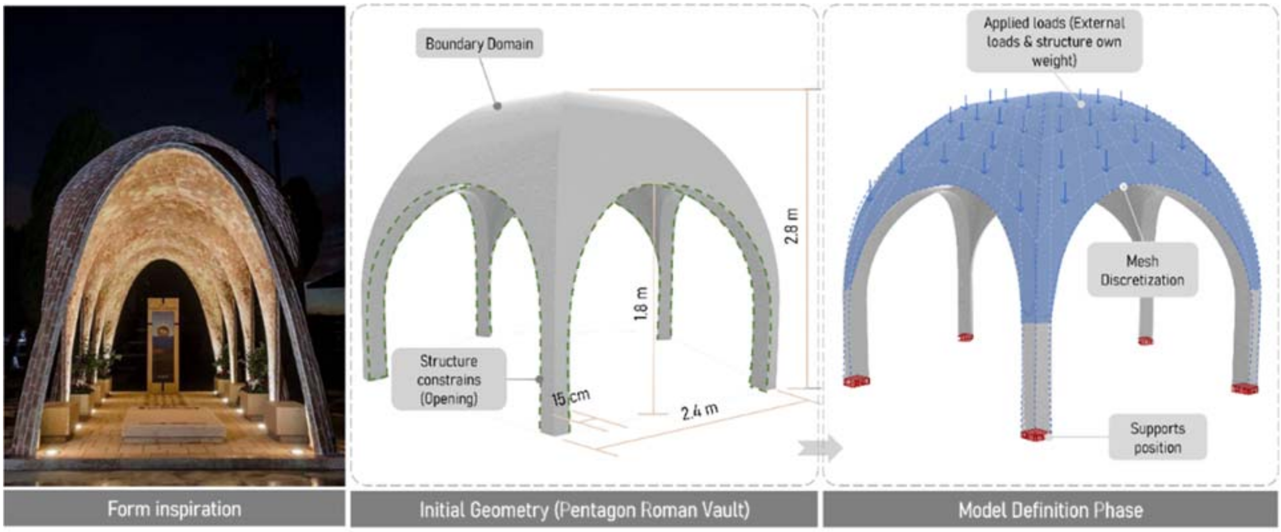


Fig. 4. Case study's model definition phase (created by the authors)

Applying the topology optimization method

The phase under consideration holds significant importance within the form-finding process, as it involves the application of topological optimization techniques. The first step involves selecting the appropriate software. The analytical process subsequently employs the finite element method (FEM) and facilitates material reduction through the software. This results in the generation of several iterations. Ultimately, the selection of the definitive design depends on the final decision. It is worth noting that an increase in the number of optimization iterations directly correlates with a higher level of accuracy in the outcome. If necessary, the designer has the ability to refine the output-optimized design, as depicted in Fig. 5.

The selected case study involves the use of the tOpos plugin in Rhino-Grasshopper, which utilizes the SIMP (Solid Isotropic Material with Penalization) technique. The optimization iteration numbers were set to 50, 100, 200, 300, and 500, as can be seen in Fig. 6. The final design selected is the one obtained after 500 iterations of optimization, as it has been determined to be the most accurate. The finite element approach, as depicted in Fig. 7, was implemented using tOpos plugin.

Post-modification

The final stage of the form-finding process involves post-modification. During this step, the results obtained from the topological optimization process are adjusted and prepared for the subsequent production procedure. The above-mentioned phase may undergo modification based on whether the structure in question is continuum or discrete in nature. In the case of a continuum structure, the post-modification process involves two consecutive steps, namely mesh smoothing and overhang reduction. Overhang reduction refers to modifying a model to reduce the presence of steep printing angles. If the structure is discrete, the post-modification phase is established during the cell design process with the objective of determining the cell's orientation, topology, and thickness. Subsequently, the model undergoes fine-

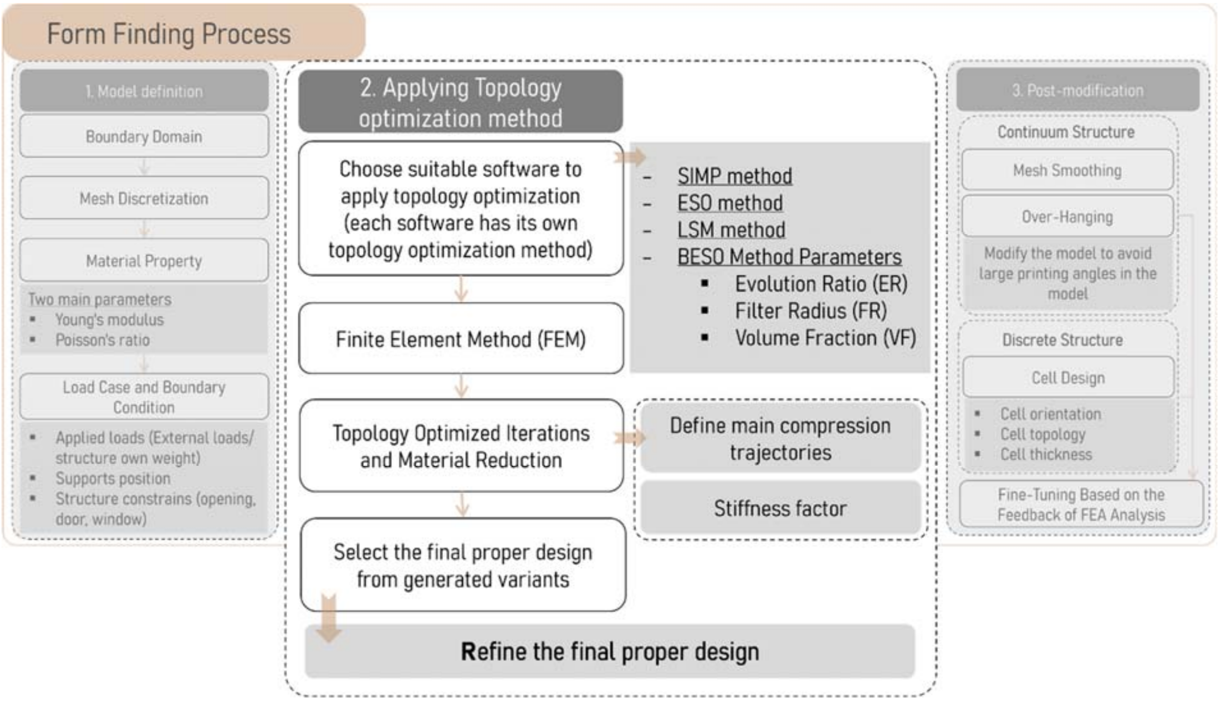


Fig. 5. Workflow of the form-finding process, applying topology optimization method phase (created by the authors)

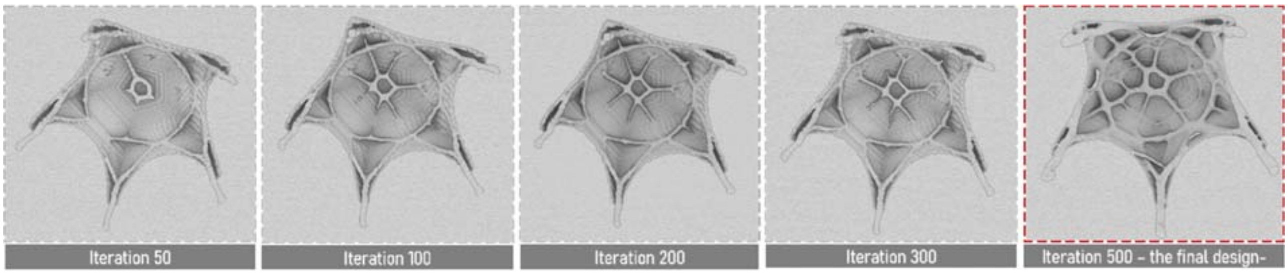


Fig. 6. Topology optimized iterations and material reduction (created by the authors)

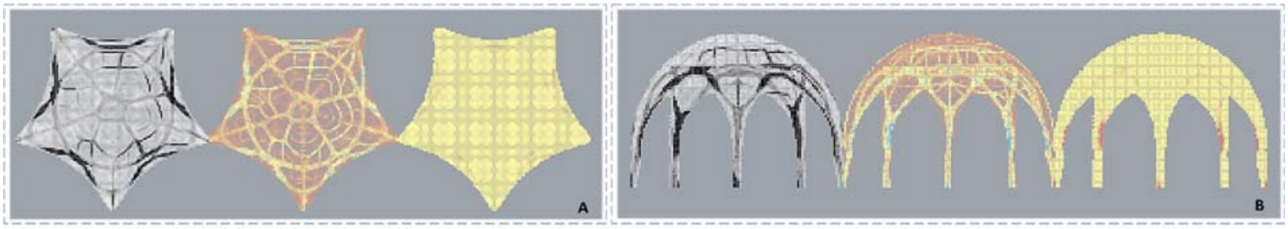


Fig. 7. Topology optimization and FEA. a. Layout; b. Elevation by tOpos plugin in Rhino-Grasshopper (created by the authors)

tuning through the incorporation of inputs obtained from the FEA, as shown in Fig. 8.

The case study model exhibits a continuum structure, thereby necessitating the use of a mesh smoothing technique. Upon reaching the conclusion of this stage, all advancements related to the case study have been finalized, resulting in the production of the ultimate outcome, as depicted in Fig. 9.

The graphical representation in Fig. 10 illustrates the disparity between the basic geometry and the

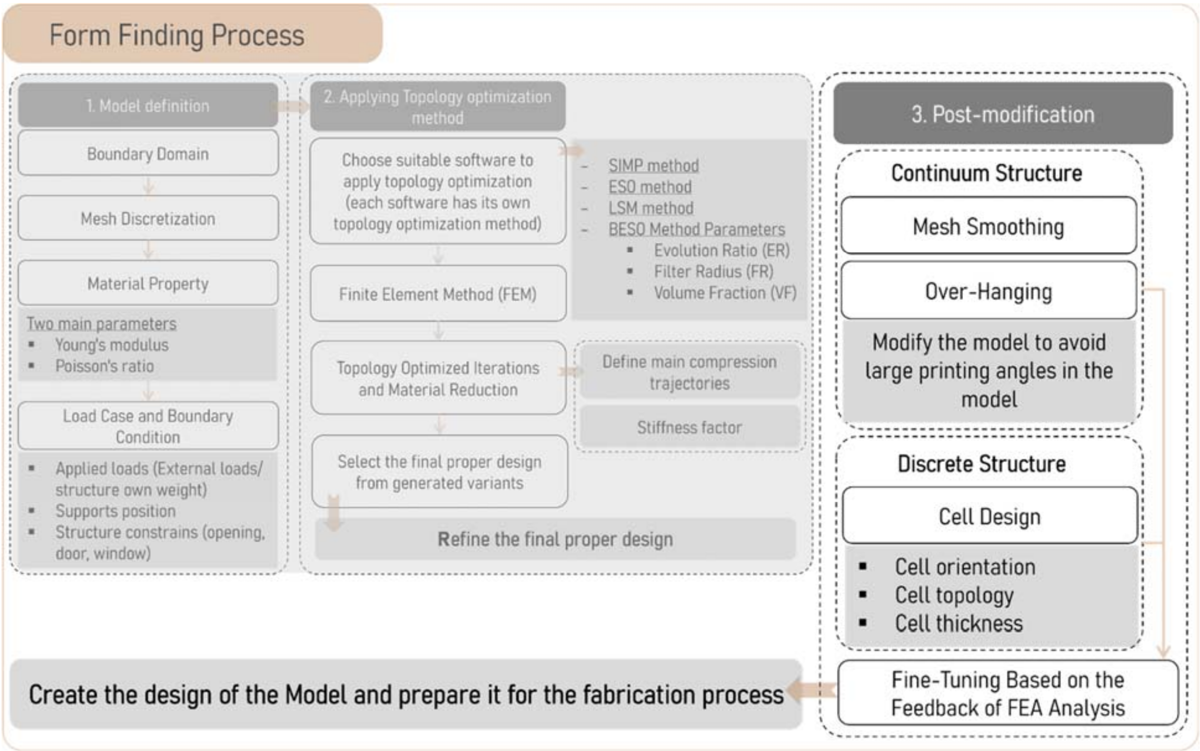


Fig. 8. Workflow of the form-finding process, post-modification phase (created by the authors)

Fig. 9. Final optimized model after the form-finding process (created by the authors)

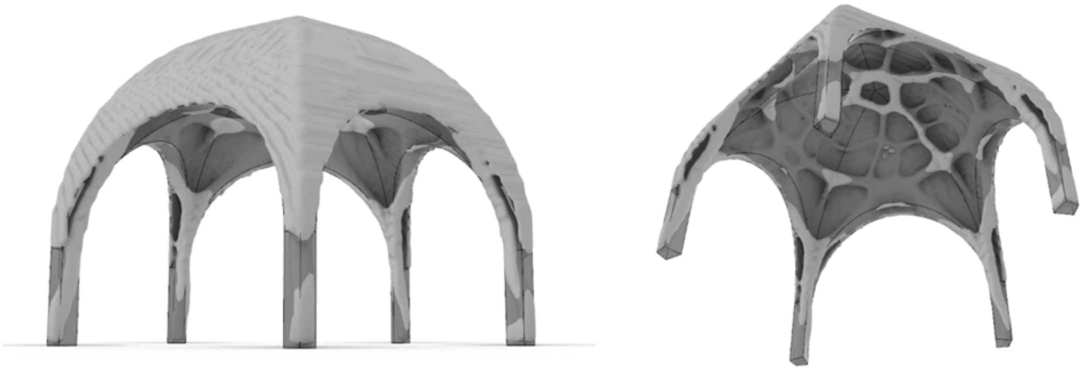


Fig. 10. Initial geometry and final optimized design shown together, illustrating the material reduction that occurred from topology optimization (created by the authors)

optimized model, highlighting the extent of material reduction resulting from the process of topology optimization. The design's aesthetic draws inspiration from natural elements and is characterized by an abundance of organic forms. Fig. 11 illustrates the comprehensive script used in the tOpos plugin within the Grasshopper environment. In the context of this study, it can be observed that each phase is associated with a specific color. The color beige is assigned to the model definition phase, blue is designated for the application of the topology optimization method, and gray is utilized to represent the post-modification phase.

Fabrication Process

The fabrication process has four distinct phases, including the selection of an appropriate digital manufacturing technique, the preparation and testing of materials, the design of fabrication and joints, and the final assembly phase. The choice of digital manufacturing technology is a crucial aspect of the fabrication process. Next, the appropriate material is selected for this specific approach. In some cases, it becomes crucial to prioritize material selection over fabrication techniques, or alternatively, the choice of technique is contingent upon the designated material. Therefore, in such scenarios, the selection of materials takes precedence over the selection of fabrication techniques. The material preparation and testing process involves three distinct steps: material comparison, anisotropy testing, and material and printing refinement. During the fabrication and joint design phase, it is necessary to divide the model into components that can fit inside the working area of the printing machine. It is also important to establish a comprehensive system for joints, encompassing various forms of connections. During the assembly process, it is imperative to develop a tectonic system that effectively partitions the structure into smaller components, known as pre-assembled clusters. It is also crucial to establish a well-defined assembly sequence for these clusters in order to successfully install the entire structure, as can be seen in Fig. 12.

The optimized output model for the case study was printed using a small-scale desktop 3D printer (Ender-3 V2) and PLA+ filament material. Fig. 13 shows the printing process, and Fig. 14 shows the final printed optimized model.

The following content presents a comprehensive framework for implementing topology optimization in the design of lightweight structures.

Conclusion

This study used analytical and deductive methodologies. The analytical approach involved conducting a comparative analysis of six case studies on lightweight structures. These structures were optimized using a specific topology optimization method at different stages. The analysis considered such factors as the structural type (continuum or discrete), form-finding techniques, the specific topology optimization method employed (ranging from SIMP to BESO), the materials used, the software utilized, the fabrication techniques employed, and the overall workflow for designing and fabricating each case study. The deductive approach was used to develop a framework for applying topology optimization in lightweight structures, as demonstrated by this analytical comparison. This framework consists of two fundamental processes, namely the form-finding process and the fabrication process (Fig. 15). Additionally, it is crucial to thoroughly analyze and comprehensively examine every step involved in each individual procedure. Next, the above-mentioned framework was employed to conduct a case study on the pentagonal Roman vault and create an optimal structure in terms of topology.

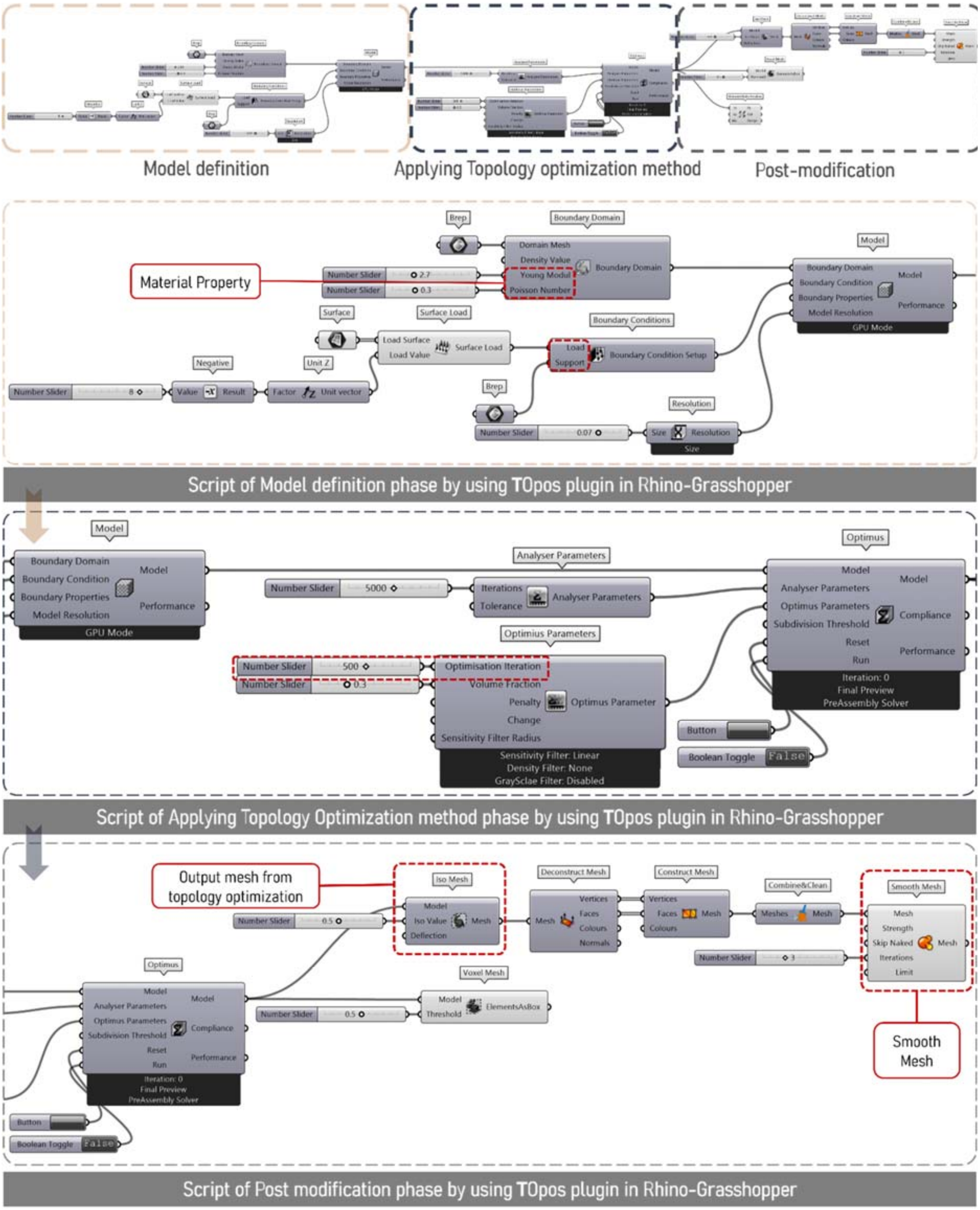


Fig. 11. Overall script for the form-finding process using the tOpos plugin in Rhino-Grasshopper (created by the authors)

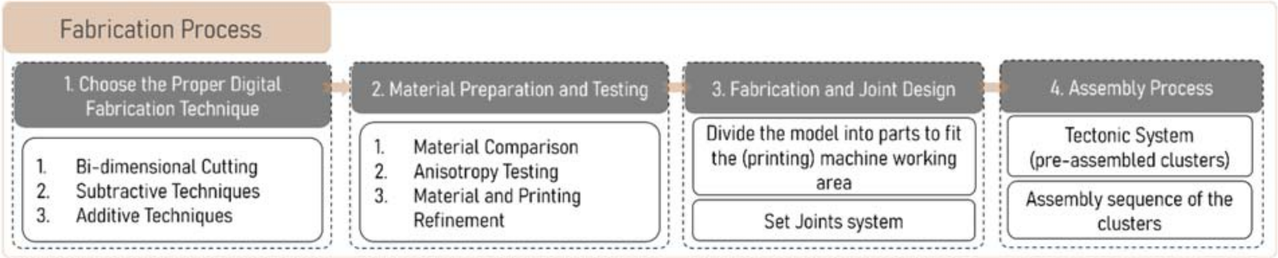


Fig. 12. Workflow of the fabrication process (created by the authors)

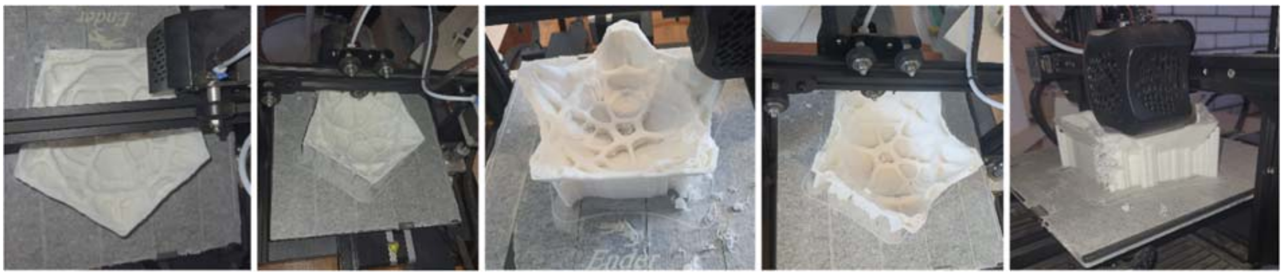


Fig. 13. Model printing process using a small-scale desktop 3D printer

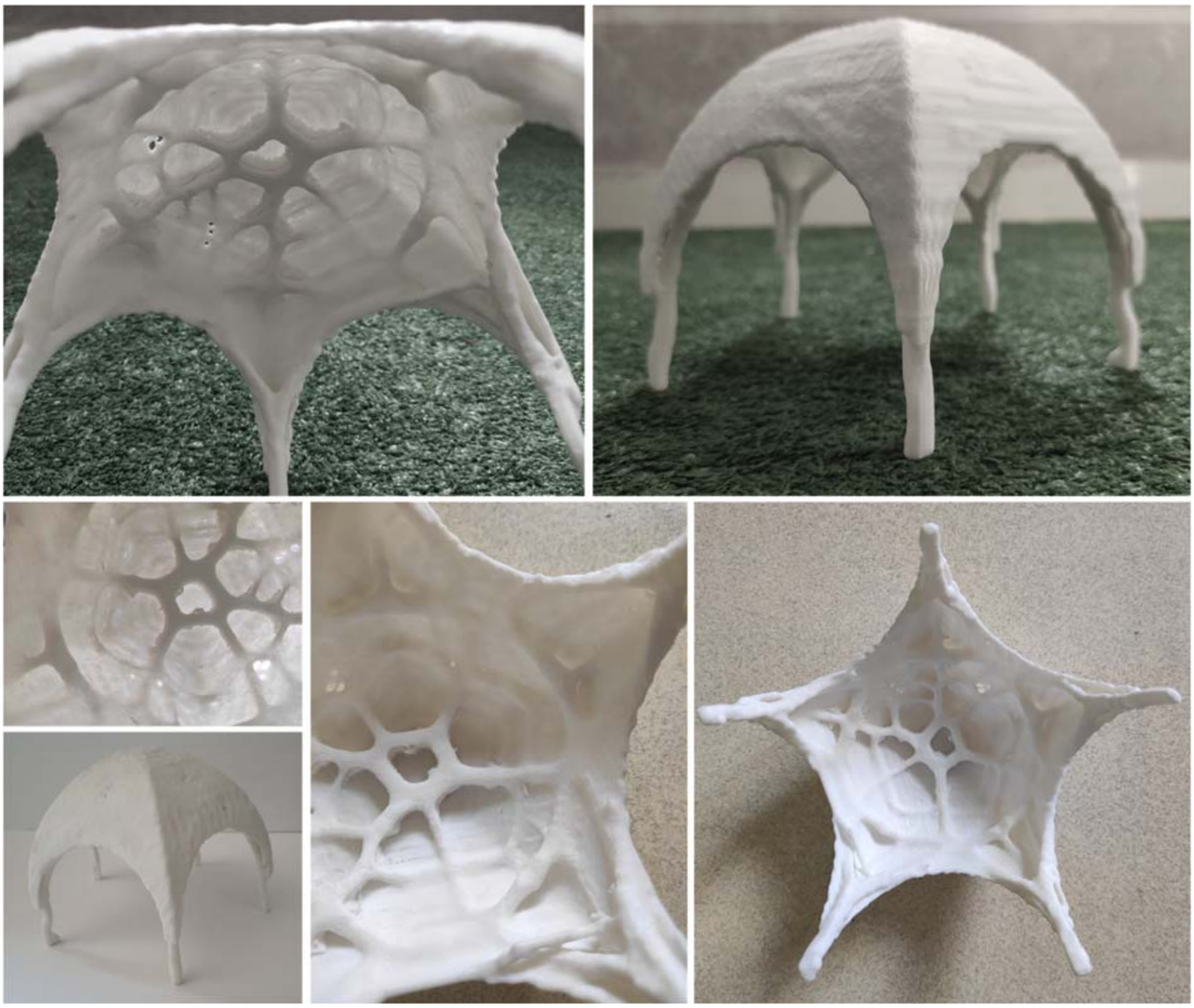


Fig. 14. Final printed optimized model

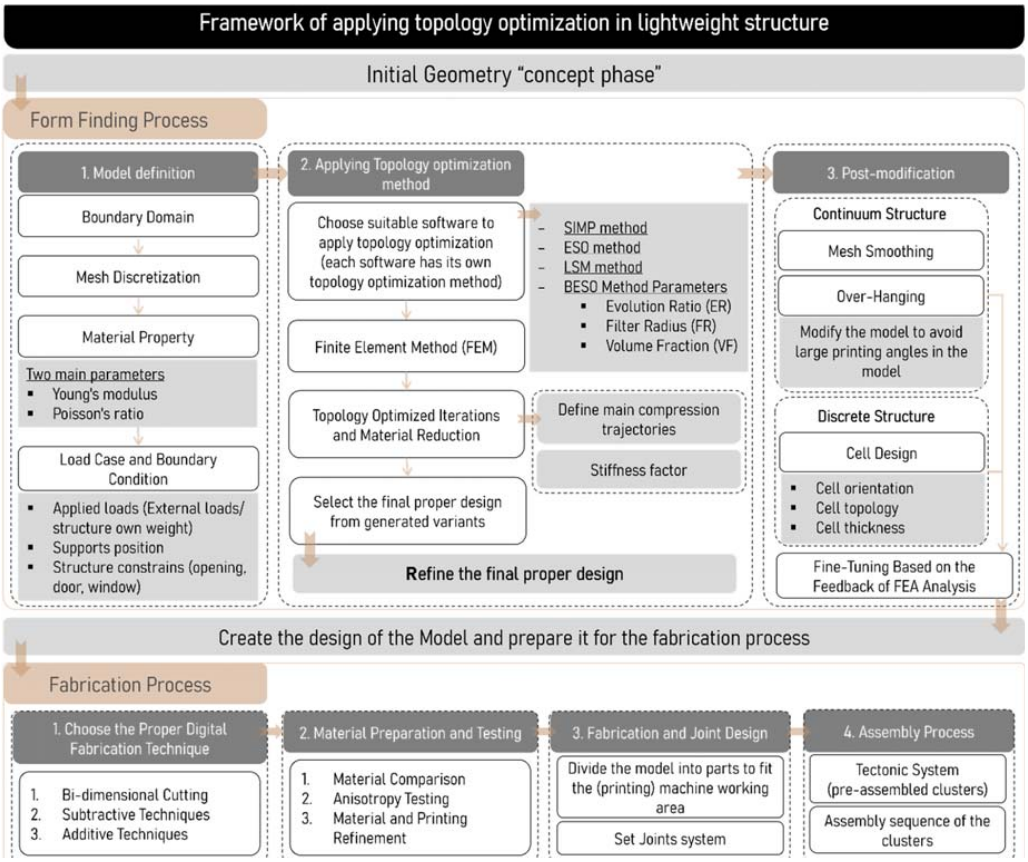


Fig. 15. Framework for applying topology optimization in lightweight structures (created by the authors)

References

architizer.com (2023). *Mortuary Chapel for the Soriano Manzanet family*. [online] Available at: https://architizer.com/projects/mortuary-chapel-for-the-soriano-manzanet-family-1/ [Date accessed September 25, 2023].

Bao, D. W., Yan, X., Snooks, R., and Xie, Y. M. (2019). Design and construction of an innovative pavilion using topological optimization and robotic fabrication. In: *IASS Symposium 2019 - 60th Anniversary Symposium of the International Association for Shell and Spatial Structures; Structural Membranes 2019 - 9th International Conference on Textile Composites and Inflatable Structures, FORM and FORCE*, October 7–10, 2019, Barcelona, Spain, pp. 485–492.

Bao, D. W., Yan, X., Snooks, R., and Xie, Y. M. (2020). Bioinspired generative architectural design form-finding and advanced robotic fabrication based on structural performance. In: Yuan, P. F., Xie, M., Leach, N., Yao, J., and Wang, X. (eds.). *Architectural Intelligence*. Singapore: Springer, pp. 147–170. DOI: 10.1007/978-981-15-6568-7_10.

Bao, D. W., Yan, X., and Xie, Y. M. (2022). Fabricating topologically optimized tree-like pavilions using large-scale robotic 3D printing techniques. *Journal of the International Association for Shell and Spatial Structures*, Vol. 63, No. 2, pp. 122–131. DOI: 10.20898/j.iass.2022.009.

Bhooshan, S. (2017). Parametric design thinking: A case-study of practice-embedded architectural research. *Design Studies*, Vol. 52, pp. 115–143. DOI: 10.1016/j.destud.2017.05.003.

Chen, Z., Zhang, L., and Yuan, P. F. (2019). Innovative design approach to optimized performance on large-scale robotic 3D-printed spatial structure. In: *Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019*, Vol. 2. Hong Kong: Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), pp. 451–460.

Dahy, H., Petrs, J., and Baszynski, P. (2020). Biocomposites from annually renewable resources displaying vision of future sustainable architecture: design and fabrication of two 1:1 demonstrators. In: Burry, J., Sabin, J., Sheil, B., and Skavara, M. (eds.). *Fabricate 2020: Making Resilient Architecture*. London: UCL Press, pp. 66–73. DOI: 10.2307/j.ctv13xpsvw.13.

Javadi Moghaddam, J., Momeni, D., and Zarei, G. (2023). Application of topology optimization method for the gothic greenhouse design. *World Journal of Engineering*, Vol. 20, Issue 3, pp. 496–509. DOI: 10.1108/WJE-03-2021-0191.

Liu, K., Bai, Y., Yao, S., and Luan, S. (2022). Topology optimization of shell-infill structures for natural frequencies. *Engineering Computations*, Vol. 39, No. 8, pp. 3083–3107. DOI: 10.1108/EC-03-2022-0135.

Liu, Y., Li, Z., Wei, P., and Chen, S. (2019). Generating support structures for additive manufacturing with continuum topology optimization methods. *Rapid Prototyping Journal*, Vol. 25, No. 2, pp. 232–246. DOI: 10.1108/RPJ-10-2017-0213.

Louth, H., Reeves, D., Bhooshan, S., Schumacher, P., and Koren, B. (2017). A prefabricated dining pavilion: using structural skeletons, developable offset meshes and kerf-cut bent sheet materials. In: Menges, A., Sheil, B., Glynn, R., and Skavara, M. (eds.). *Fabricate 2017*. London: UCL Press, pp. 58–67. DOI: 10.2307/j.ctt1n7qkg7.12.

Ma, J., Li, Z., Zhao, Z.-L., and Xie, Y. M. (2021). Creating novel furniture through topology optimization and advanced manufacturing. *Rapid Prototyping Journal*, Vol. 27, No. 9, pp. 1749–1758. DOI: 10.1108/RPJ-03-2021-0047.

Martins, V. C., Cutajar, S., van der Hoven, C., Baszyński, P., and Dahy, H. (2020). FlexFlax stool: Validation of moldless fabrication of complex spatial forms of natural fiber-reinforced polymer (NFRP) structures through an integrative approach of tailored fiber placement and coreless filament winding techniques. *Applied Sciences*, Vol. 10, Issue 9, 3278. DOI: 10.3390/app10093278.

Naboni, R., Breseghello, L., and Kunic, A. (2019). Multi-scale design and fabrication of the Trabeculae Pavilion. *Additive Manufacturing*, Vol. 27, pp. 305–317. DOI: 10.1016/j.addma.2019.03.005.

Rihaczek, G., Klammer, M., Başnak, O., Petrš, J., Grisin, B., Dahy, H., Carosella, S., and Middendorf, P. (2020). Curved foldable tailored fiber reinforcements for moldless customized bio-composite structures. Proof of concept: biomimetic NFRP stools. *Polymers*, Vol. 12, Issue 9, 2000. DOI: 10.3390/polym12092000.

Sigmund, O. and Maute, K. (2013). Topology optimization approaches: A comparative review. *Structural and Multidisciplinary Optimization*, Vol. 48, Issue 6, pp. 1031–1055. DOI: 10.1007/s00158-013-0978-6.

Tedeschi, A. (2014). *AAD_algorithms-aided design: parametric strategies using Grasshopper*. Brienza: Le Penseur, 496 p.

Woo, S. J. (2020). *An architectural implementation of topology optimization guided discrete structures with customized geometric constraints*. MSc Thesis in Arhitecture.

Xie, Y. M. (2022). Generalized topology optimization for architectural design. *Architectural Intelligence*, Vol. 1, Issue 1, 2. DOI: 10.1007/s44223-022-00003-y.

Yıldırım, E. (2022). Topology optimization in architecture practices. In: Biçer, Ö. P. and Gürani, F. Y. (eds.). *Research & Reviews in Architecture, Planning and Design*. Ankara: Gece, pp. 117–137.

ПРИНЦИПИАЛЬНО НОВАЯ СХЕМА ПРИМЕНЕНИЯ ТОПОЛОГИЧЕСКОЙ ОПТИМИЗАЦИИ В ОБЛЕГЧЕННЫХ КОНСТРУКЦИЯХ

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Аннотация

Введение: топологическая оптимизация широко используется в инженерных разработках и проектировании строительных конструкций. В области архитектуры, особенно в контексте облегченных конструкций, для полноценного использования этого метода необходимы серьезные навыки в программировании. **Цель исследования** — сформировать базовую схему, способствующую беспрепятственному применению топологической оптимизации при проектировании архитекторами облегченных конструкций. **Методы**: в данной работе для анализа шести примеров применения топологической оптимизации в различных облегченных конструкциях использовался дедуктивный метод. Анализ проводился на основе заранее определенного набора критериев. Кроме того, дедуктивный метод использовался для формирования схемы реализации топологической оптимизации при проектировании облегченных конструкций. Данная схема была использована для создания оптимизированной облегченной конструкции (пентагональный цилиндрический свод). **Выводы**: анализ примеров проводился с учетом двух процессов — процесса поиска формы и процесса изготовления. Исследование было направлено на определение методологической основы, задействованной в процессе проектирования и изготовления по каждому из примеров. Основополагающая схема была разработана на основе аналитического сравнения шести примеров. Данная схема позволяет создавать оптимизированные облегченные конструкции. **Новизна**: в данном исследовании представлены значимые результаты в области топологической оптимизации и ее использования в облегченных конструкциях, открывающие широкие возможности для архитекторов, стремящихся к созданию эстетически привлекательных и оригинальных архитектурных форм, в которых приоритетом является высокая жесткость и небольшой вес.

Ключевые слова: облегченные конструкции, топологическая оптимизация, аддитивные технологии.