Potential Contributions of Topology Optimization for Building Structures: A Redesign Case Study on Saint Voukolos Church



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Received: 10.06.2022
Accepted: 25.06.2022
DOI: 10.17932/IAU.ARCH.2015.017/arch_v08i1005

Abstract: Topology optimization, which has been used in many sectors for a long time, has recently become one of the new research and application trends in the field of architecture. Topology optimization, which can be considered as a part of additive manufacturing, is one of the initiatives to reduce the use of materials during the construction phase by deciding on the architectural design processes. The topology optimization applied according to the load distribution of the structure also reveals unique forms for each structure. This paper aims to examine the potential contributions of a structure designed with topology optimization to the structure in terms of material and form and to create an exemplary model in this context. For this purpose, Saint Voukolos Church, one of the historical masonry buildings in İzmir/ Turkey, was selected and redesigned with topology optimization. The topological optimization of this structure, which was 3D modeled in Rhinoceros®, was made with tOpos®, and two (existing and redesigned) designs were compared in terms of structure, material, and form. As a result, it has been seen that the topologically optimized proposed structure can be built with much less material than the existing structure and more original forms can emerge.

Keywords: *Topology optimization, structural optimization, masonry, architecture*

Yapılar için Topoloji Optimizasyonunun Potansiyel Katkıları:Aziz Vukolos Kilisesi'nin Yeniden Tasarım Çalışması

Özet: Uzun süredir birçok sektörde kullanılan topoloji optimizasyonu, son zamanlarda mimarlık alanında yeni araştırma ve uygulama trendlerinden biri haline geldi. Eklemeli üretimin bir parçası olarak değerlendirilebilecek topoloji optimizasyonu, mimari tasarım süreçlerine karar vererek inşaat aşamasında malzeme kullanımını azaltmaya yönelik girişimlerden biridir. Yapının yük dağılımına göre uygulanan topoloji optimizasyonu da her yapı için kendine özgü formlar ortaya çıkarmaktadır. Bu makale, topoloji optimizasyonu ile tasarlanmış bir yapının, yapıya malzeme ve form açısından potansiyel katkılarını incelemeyi ve bu bağlamda örnek bir model oluşturmayı amaçlamaktadır. Bu amaçla İzmir/Türkiye'deki tarihi yığma yapılardan biri olan Aziz Vukolos Kilisesi seçilmiş ve topoloji optimizasyonu ile yeniden tasarlanmıştır. Rhinoceros®'ta 3 boyutlu olarak modellenen bu yapının topolojik optimizasyonu tOpos® ile yapılmış ve iki (mevcut ve yeniden tasarlanmış) tasarım; yapı, malzeme ve form açısından karşılaştırılmıştır. Sonuç olarak, topolojik olarak optimize edilmiş önerilen yapının mevcut yapıya göre çok daha az malzeme ile inşa edilebileceği ve daha özgün formların ortaya çıkabileceği görülmüştür.

Anahtar kelimeler: *Topoloji optimizasyonu, yapısal optimizasyon, yığma, mimarlık*

1. INTRODUCTION

Depending on the developing technology in design software, the building or building elements are also differentiated and become unique. Finding the form that the building will take under dead or dynamic loads has also emerged depending on the development of these technologies. According to Beghini et al. (2014) "Topology optimization is a mathematical, usually (but not always) gradient-based design tool which determines the location in a design domain to place material based on the loads and boundary conditions for a specific objective (i.e., a target deflection, compliance, etc.)."[3]. In other words, topology optimization in architectural use is a method for reducing the material used to construct of structures with specified design criteria. In the historical process, churches built in the gothic style can be considered the first examples of topology optimization in architecture. Gaudi's La Sagrada Familia and Eiffel's Eiffel tower designs are also among the most popular examples. While the main purpose of topology optimization for structures is to reduce unnecessary material during construction, another advantage is that each structure gives unique forms according to the determined parameters. Reducing the energy consumed with the savings from raw materials also ensures that these buildings are kind of sustainable. This study examines the potential contributions of structures designed with topology optimization in terms of material and form to the structure and the environment. In this context, after examining the previously studied topology optimization prototypes, building elements, and building samples designed and applied with topology optimization, what would have happened if Saint Voukolos Church in İzmir had been designed with topology optimization was examined. This selected church was modeled in Rhinoceros® and topologically optimized in tOpos®, one of the Grasshopper plugins. Optimization of the form that the church took under its load is seen in the 3rd chapter. The comparison of the existing structure and the optimized structure is examined in the conclusion part.

2. LITERATURE REVİEW

In this chapter, in addition to the prototypes and structural elements that have been studied with topology optimization, examples that have been built such as the Unikabeton project, the Qatar National Convention Center and the Akutagawa River Side Office Building will be examined.

Prototypes and Structural elements

The first of the examined samples belongs to Peng. He examined the results obtained by varying the height between the support and the beam, keeping the load, span, and thickness constant. It can be seen in Figure 1 that there is no main trunk formation in a, b, and c. Only branches can be seen [4].

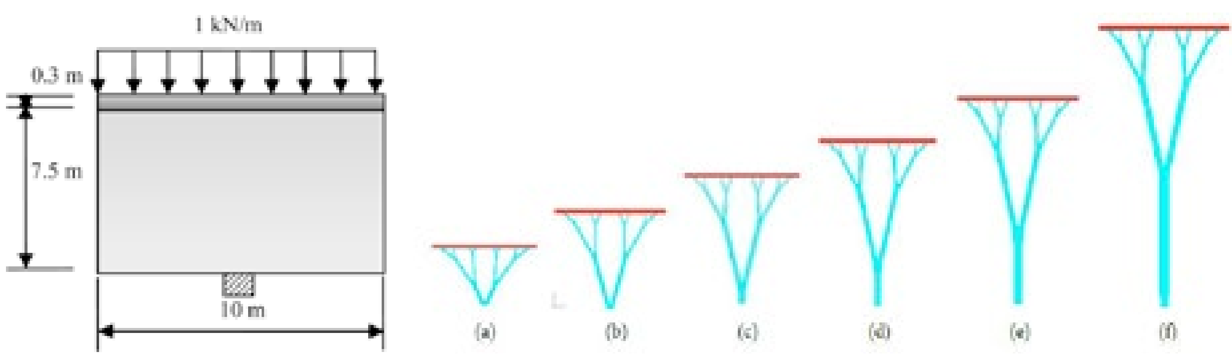

Figure 1. Topologically optimized dendriforms under different heights [4]

Another study by Peng is the topological optimization of a slab with multiple support points as shown in Figure 2. It has been observed that the column designs that transfer the load to the corner and middle supports of the slab on which the distributed load is applied differ [4].

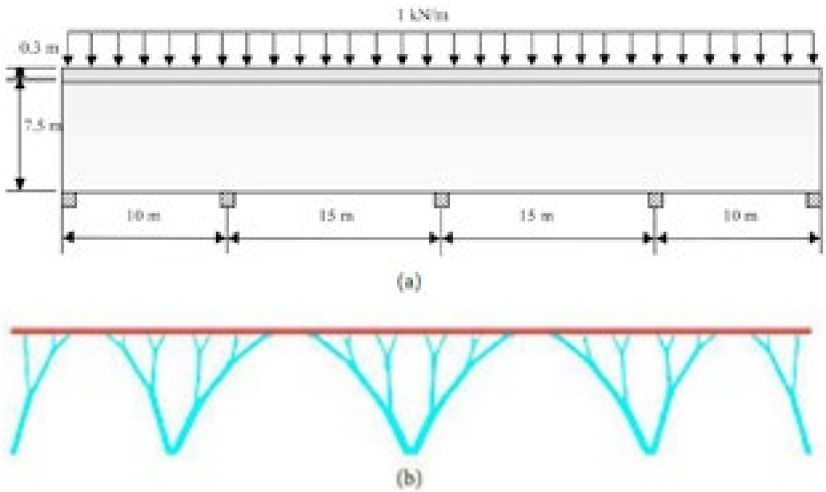

Figure 2. a) Design inputs b) Topologically optimized columns [4]

Bialkowski's study, on the other hand, has been examined again as a structural element. The behavior of the slab under 2 kN/m² has been studied on tOpos® by determining the point-supported state of the floor in certain dimensions in the first case (a), all the walls touch the ground in the second case (b), and the openings in the third case (c) as seen in Figure 3 [5].

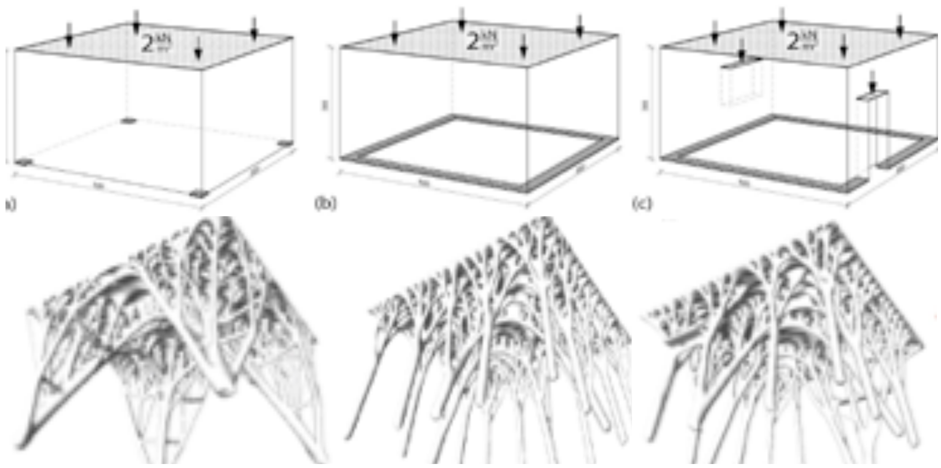

Figure 3. Boundary conditions and tOpos® results [5]

Oliveira and others' studies are on the construction themselves. After the mass study of the structure whose design criteria were determined, the support and load conditions were determined, and the results of the optimization were interpreted, and the final designs were obtained. Their first study was on high-rise buildings and their second study was on a bridge design. As seen in Figure 4a and 4b, the high-rise building, and the bridge optimization are trying to find optimal truss systems [6].

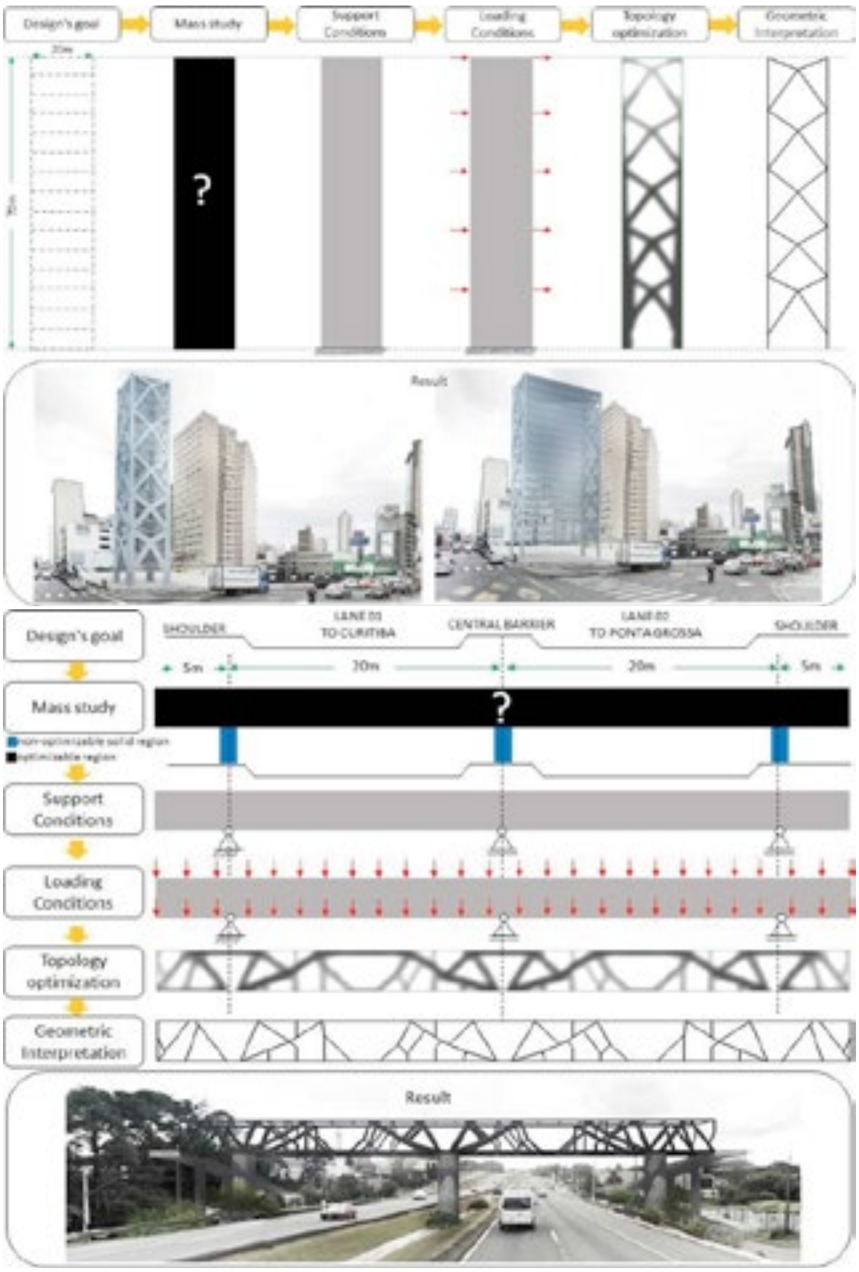

Figure 4. a) A high-rise building's truss optimization b) A bridge's truss optimization [6]

Unikabeton Project

Unikabeton project (Figure 5) is a topology optimization project for concrete structures designed and constructed by the Aarhus School of Architecture in 2007 [7]. EPSs were shaped with robotic CNC milling for the project, and these materials were used as molds. With robot CNC milling, the project explored how such structures can be realized efficiently with high precision and ease of mold making [8].

Figure 5. The constructed slab of the Unikabeton project [7]

12 x 6 x 3.3-meter concrete structure in the form of an asymmetrical, double-curved slab with triple column support was designed and optimized by topology optimization. According to the designers, this project achieved 70% material savings compared to the non-topology optimized structure [7].

Qatar National Convention Centre

Qatar National Convention Centre was designed by Arata Isozaki and, its construction was completed in 2011. The final design is 250 m long, 30 m wide and 20 m high. The tree-like structure, as seen in Figure 6 obtained in shape and topology optimization is formed by pipes supported by steel bars [9]. The dendriforms-like structure is the most challenging part of the structure design. Each component of the dendriforms must conform to optimal ways to transmit loads and also meet the functional requirements of the building [4].

Figure 6. The constructed slab of the Unikabeton project
Qatar National Convention Center and its carrier steel pipes [10]

Akutagawa River Side Office Building

The first example of ESO (Evolutionary Structural Optimization) being implemented is the Akutagawa River Side Office Building project in Takatsuki city. The construction of this four-story office building was completed in 2004. The ESO method has been adopted for the shape determination of the walls in this building. Two of its west and south-facing side walls were optimized using ESO and built with reinforced concrete. Dead and live loads and dynamic earthquake loads are taken into account. The results of the evolutionary design were then analyzed, and the structure was constructed as seen in Figure 7 [11].

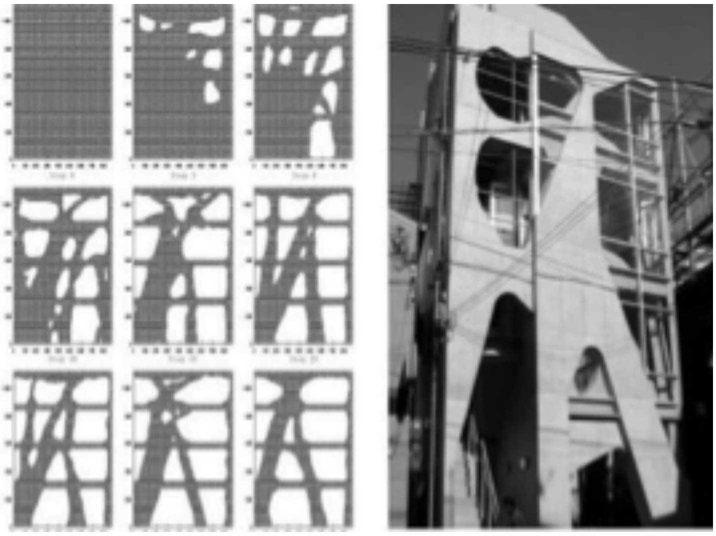

Figure 7. Akutagawa River Side Office Building's façade optimization [11]

3. CASE STUDY

As explained in the beginning part of the paper, this case study aims to show that the use of building materials can be reduced with the design that can be obtained as a result of topology optimization of an existing structure. The purpose of choosing a masonry structure is that the change in the form of the volume can be directly observed. The desired point is to reduce the use of materials necessary for the structure to stand under its load. In this context, Izmir Saint Voukolos Church which can be seen in Figure 8, one of the oldest masonry buildings in İzmir, was chosen. The results obtained for this masonry structure which was made of stone and brick will be compared with the existing structure in the conclusion.

Figure 8. Saint Voukolos Church [12]

The church is a Greek church built in Izmir in 1886. After the Greeks left the city with the population exchange, it was used for different functions such as a museum, opera house, and warehouse. After the restoration works carried out in 2010, it hosts various cultural and artistic events. The load-bearing system of the building, which was built using stone and brick, is masonry. The plan scheme of this building, which was designed with the traditional church logic, is in the form of a cross and there is an apse [13]. At the entrance of the church, there is a welcoming place consisting of arched columns. There are no structural elements that are obscuring in the interior. The church's roof consists of vaults, and in the middle of the roof is a cone-shaped projection designed for the natural lighting of the church.

The methodology of this study is as follows. Section and plan of the church obtained from the restoration department of IZTECH are seen in Figures 9(a) and 9(b). Based on these drawings, 3D modeling was done. The 3D model of this church was modeled in Rhinoceros® on a 1/1 scale concerning its plan and sections. The openings placed in the desired places in the design of the church have been preserved and shown in the model. After modeling the vaults and the cone-shaped volume placed on the roof for natural lighting, the model is ready for optimization.

Figure 9. a) Section of Saint Voukolos Church b) Ground floor plan of the church [14]

After finishing the model, the topology optimization part was carried on. tOpos® is a 3D Topology Optimization plugin for Grasshopper. "It is using GPU for computation acceleration. It is based on CUDA technology provided by NVIDIA. The current version of tOpos® requires NVIDIA graphic card with Cuda Computation Capability (cc) higher or equal to 3.0."(food4rhino, n.d.). The topology optimization code for this optimization can be seen in Figure 10.

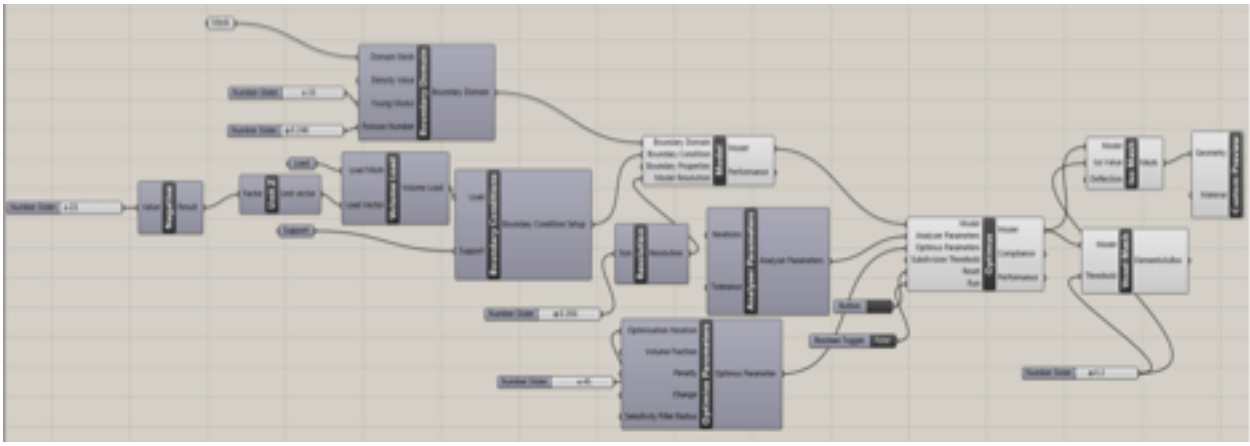

Figure 10. Grasshopper/ tOpos® code of the optimization

First, the structure and its features are defined. In Boundary Domain, the structure itself and its properties are defined. For example, for Young Module, the modulus of elasticity in tension or compression value of the material is defined as 33 GPA and for Poisson Number, the deformation in the material in a direction perpendicular to the direction of the applied force value is defined as 0.246. Then, the support and load conditions (as 23 kN/m²) are defined. In this part, since the form that the structure will take under its own load was wanted to be examined, distributed load tool was used. Then, optimization parameters were determined, such as iteration of optimization and resolution of the model. It has also been determined how to define the form that will be formed after the optimization is completed. Lastly, obtained optimized model has been softened with Weaverbird which is also one of the Grasshopper plugins. However, it should be noted that the obtained result will vary according to the parameters you defined in the tOpos®. For example, while young modulus and Poisson numbers will vary according to the building materials that are used in the construction; some parameters such as iteration, resolution, and how to define the form belong to the designers' decision.

<u>Case Study Results</u>

The form that the building will take under its load is shown in the figures below. Instead of using all the walls as load-bearing elements, the use of materials has been reduced with the help of branches and columns supporting and transferring the roof's load to the ground. One of the important points that should not be forgotten here is that this optimization focuses on the carrier system rather than defining a closed space. In Figure 11, the result of the optimization obtained by using the voxel mesh tool is seen.

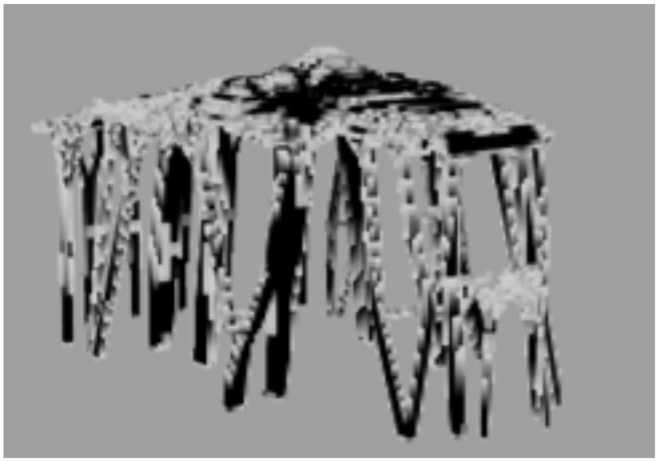

Figure 11. The first rough result from tOpos®

To make it more vivid and to be more defined architecturally, its softened versions with the Weaverbird plugin can be seen from different angles in Figure 12.

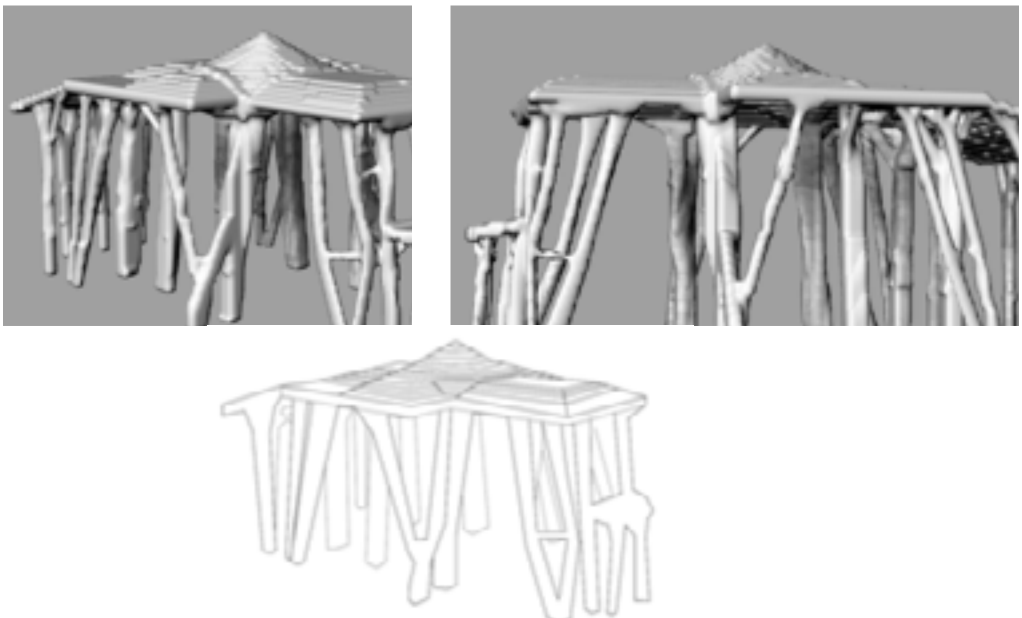

Figure 12. Softened results from Weaverbird

4. CONCLUSION

It is known that raw material shortages and our energy dependence have increased with technology. For this reason, there are new applications and research in the fields of architecture and construction, as there are in every sector. In particular, designs with a sustainable approach are among the most studied topics. This paper examines structures designed and applied with topology optimization to reduce the use of materials and energy required for structures, and topology optimization is made on a selected church.

As a result of the church's topology optimization, while the volume of the material used in the building was 1375.7 cubic meters at the beginning, it is 518.47 cubic meters when optimized according to the defined variable parameters. Also, according to the defined parameters, while there were openings in 17.1% of the walls at the beginning, there was 48.7% opening in the model obtained by optimization.

Thus, designing the forms of the structures according to the load distribution minimizes the use of materials as seen in the examples and case study. In addition, it has led to unique designs for each structure, depending on the strength forces that are different for each structure. This has been achieved by ensuring the originality of the structures by connecting them to the strength forces.

Due to the inadequacy of existing computers in optimization, the final products in this study are shown with diagrammatic models. However, in future studies, the result can be expressed in an architectural style by making material definitions for the products.

Acknowledgments

We would like to express our special thanks and gratitude to Furkan Şahin for helping us with the model and creating the code part regardless of day or night. Also, we thank Prof. Dr. Başak İpekoğlu for sharing the church's section and plans.

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