



## Topology Optimization by the use of 3D Printing Technology in the Product Design Process

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Received 06 August 2020; Revised 14 October 2020; Accepted 19 October 2020; Published 01 December 2020

### Abstract

The design process of a new product includes various stages, one of which is the evaluation of an idea for prototype manufacturing. The use of additive manufacturing is the most efficient and effective method for producing prototypes. In order to maximize the benefits from the use of additive manufacturing, we should choose the suitable printing parameters. The inner wall thickness is a vital parameter for defining the quantity of raw material used and the model solidity. Depending on the selected technique of additive manufacturing, the thickness of the inner wall may differ. In this study, we initially print furniture models with different wall thicknesses using the Inject Binder technique, and then we check their durability and resilience through compression tests. Evaluating the study results indicates the hollow printed specimens have high durability during compression tests and can be used to evaluate a design idea. Using the facts derived from lab tests, we perform Topology Optimization studies under different circumstances to evaluate the method and come up with the optimal design solution. Initially, the Topology Optimization study concerned only the table surface and not the whole model. The following studies were performed for the whole model, with different constraints and load cases defined. Then, the optimized models are redesigned in order to improve their durability. The performed studies show that Topology Optimization is a powerful tool, which is able to support the designers/ engineers to take the right decision during the design process.

**Keywords:** Additive Manufacturing; Inject Binder; Optimization; Compression Test; Topology Optimization; Furniture Design.

## 1. Introduction

In the late 19<sup>th</sup> and early 20<sup>th</sup> centuries, architects and designers believed that building and product design should reflect their usage. The American architect Louis Sullivan was the strongest supporter of this principle, as he analyzed in his article titled "The Tall Office Building, Artistically Considered." The ancient Roman architect Marcus Vitruvius Pollio was of the exact same opinion [1]. Prior to WWII, modernist architects dissented from the above principle. They regarded decorative elements, which architects call ornaments, as being superfluous in modern buildings. Sullivan did not question this theory, and the buildings he designed were brimming with Art Nouveau and Celtic decorative features. Meanwhile, there was a discordance about product design: whether it should comply with market demands or focus on product functionality. For example, the American auto industry put an end to the introduction of aerodynamic forms into mass production. Some car resellers claimed that the aerodynamic shape would end up in a certain shape very similar to all vehicles, and thus automobile sales would drop [2].

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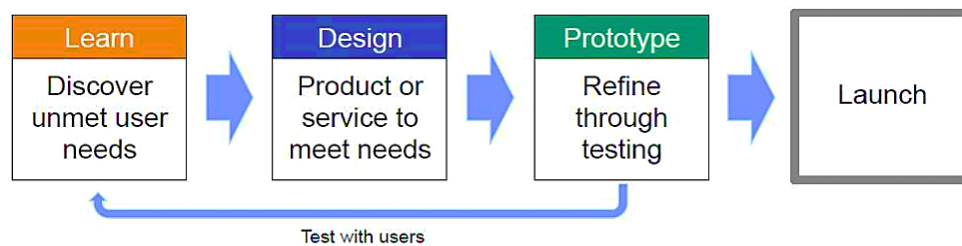
 <http://dx.doi.org/10.28991/HIJ-2020-01-04-03>

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After WWII and up until the Oxford conference on Design Methods in 1963, design was considered to be more cohesive work than a scientific procedure with distinct staying. The methodology designers adopt during the designing procedure has been the subject of investigation over the last six decades. Initially, the aspect that designers should follow a certain design process through formalized procedures or designing methods prevailed. However, this led many designers to believe that the adoption of a specific process would limit their creativity and imagination. This obstacle was overcome after the integration of brainstorming into the design process. Due to the development of the design methods, a main concern came up; the connection of design methodology to computer science as a prerequisite to thoroughly understanding and defining design [3]. In the 70's, Bill Hillier developed a new designing method, according to which the experience gained from local designing problems could be useful for addressing layer-scale issues [4, 5]. This is the first and foremost feature of this early period of design methodology. Moreover, the design problem was not clearly designed so as to adopt an optional solution. Through the definition of all possible solutions to a certain design problem, during this period, the researchers were opposed to the development of designing methods—albeit they changed their opinion over the next few years [6-8]. This can be attributed to the fact that the design methods were rapidly developed and recognized by the researchers of this period.

The last decade's product development process follows a more specific process with distinct stages (Figure 1). Through this process, designers have to ensure that the new product is well designed. In the first stage, product specifications have to be defined according to user needs. The second stage is the design stage, which includes concept design, initial 3D models, and the final 3D model. The third stage is prototype, in which designers have to produce functional physical models in order to evaluate their ideas and to check ergonomics, functionality, and product stability. Prototypes are fully functional, and end users can use them in order to give their feedback [9]. In the last decade, more and more designers and engineers have been adapting 3D printing techniques in order to create prototypes [10-12].



**Figure 1. Product design process**

Various three-dimensional printing techniques have been well developed, each one has strengths and weaknesses. Differences are based on how the individual layers have been spread to create various components, such as material melting, melt deposition, or the use of liquid materials through different technological processes. Mainly, the discussion is related to the issues of speed, cost of prototype and 3D printers, choice and cost of materials and the ability for multicolor prototypes [13].

### 1.1. Inject Binder Technique

One of the most well developed technique is 'Inject Binder'. This technique is high speed and produces objects with a relatively harsh finish. The raw material is plaster type powder, the granules of the powder are homogeneous in size and shape, showing only limited variation with respect to their size. As the particles are smaller the quality of printed part is better [14]. The process requires the use of powder as a feedstock and adhesive to achieve the agglomeration of powder grains. The printing process part involves two stages. In the first stage a slicer program divides the object geometry into number of layers and powder is speeded in each single layer. Each powder layer is sprayed selectively with an adhesive. Then a layer of fresh powder is deposited and the process repeats until all layers are printed. In the post processing stage the printed model is removed from the container and using compressed air is cleaned from the excess powder. In the sequel the printed part is sprayed with cyanoacrylate or other substances to improve part stability and surface finish [15]. The advantages of inject binder technique are: a) the lack of support structure during printing process, b) the ability to print multiple objects simultaneously, c) there is no need to use a heat source that can create residual stresses in the parts d) often is more cost effective to print bigger parts in inject binder printer than other printer type e) printing of multi-color parts [16].

### 1.2. Computational Mechanics

Computational mechanics is the scientific area that uses numerical methods to approximate the solution of engineering problems. Traditionally, the problems of engineering were solved either analytically or experimentally, computational mechanics is the third way. The development of computers over the last few decades has enabled engineers to approach problems that were impossible to solve in the past either because of the large size or the large

amount of computing time required. Computational mechanics complements analytical solutions and significantly reduces the number of required experiments. Focus on structures optimization is a significant tool in design process and especially in design of light weight structures under specific constraints. There are three different types in structural optimization: a) size optimization, b) shape optimization and c) topology optimization [17]. In size or shape optimization there is no change of the topology. In topology optimization size and shape are changed. Topology optimization methods can be based on simplified Optimality Criteria iterative reanalysis methods, Heuristics and optimization techniques [18, 19].

## 2. Materials and Methods

The current study consists from three stages, initially six specimens with different inner wall thicknesses, which are printed and then tested in a compression tester device. After that a TO study for the upper table surface is performed and the results checked with a FE analysis. Subsequent, three more TO studies with different load cases are executed. In order to check the strength of optimized models three FE analysis are executed. After evaluating the results, a redesign process starts in order to improve the structure of the models and take into account issues that could not be included in topology optimization, and, finally, the results have been checked again with respect to their strength (Figure 2).

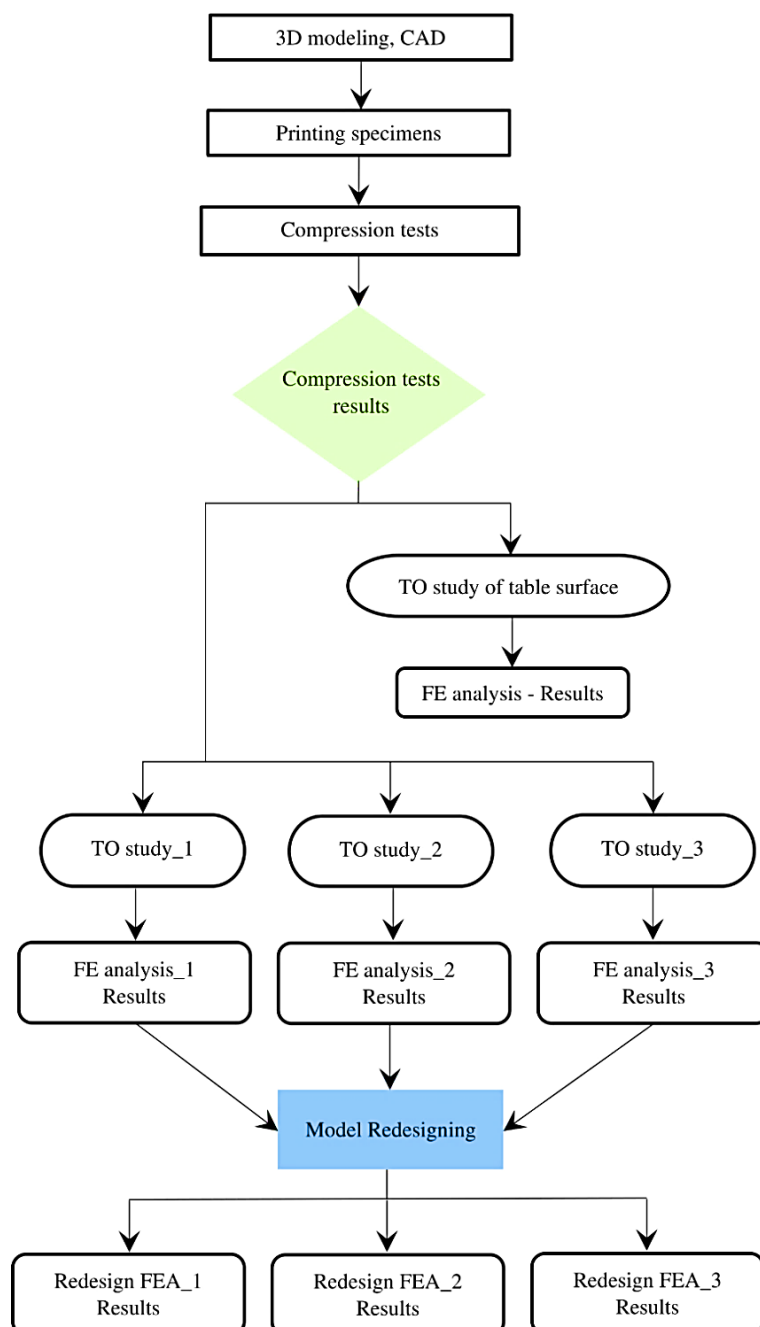


Figure 2. Research methodology flowchart

The specimens are printed in Z-450 from Z-Corp which is the ideal printer for product and architecture design prototypes. The raw materials are: a plaster-based powder (zp151) and an appropriate water based solution with 2-Pyrrolidone as a binder (zb63).

The specimens are tested in Zwick / Roell Z020 testing machine. This device is selected because of the extremely low speeds that can be set, coupled with excellent speed accuracy and offers high head movement analysis. The movement of the transverse head is guided with great precision through two steel columns, which allow accurate application of the force on the sample.

## 2.1. Topology Optimization (TO)

Topology Optimization can be a significant tool during product design process. Depending on the desired result a suitably defined objective function can be maximized or minimized. The advantages of TO are: a) creation of light weight structures b) generation of a ready-to-build part/assembly c) minimize the amount of raw material d) energy saving e) less need for natural prototypes f) reduction of physical testing g) reduced entry time to market [17]. In the domain of an optimized model, the material elastic properties compared with the density may vary so material can be permanently removed [20]. Often the optimized structure is extremely difficult to be produced by using traditional manufacturing methods like lathe, or milling and usually additive manufacturing is the appropriate production method. According to the literature, there are several articles about topology optimization in furniture design or other consumer products [21, 22]. During the TO study all boundary conditions have to be defined. The Mathematical formulation for the minimization of the objective function specified as below:

$$\text{Specify } \chi = \begin{Bmatrix} \chi_1 \\ \chi_2 \\ \vdots \\ \chi_n \end{Bmatrix} \text{ which minimize } f(x) \quad (1)$$

Where;  $g_i(x) \leq 0, i = 1, 2, \dots, m; h_j(x) = 0, j = 1, 2, \dots, n.$

Two methods have been developed for TO study. The first one is truss based and the second is volume based.

### 2.1.1. Truss Based TO Method

The truss-based or ground structure approach is based on a large number of elements relating to a grid of beams between a set of nodes in a given volume. The method initially detects which supports are necessary for the structure and determine their size. Then removes the beams that not meet the study requirements. In the results, the necessary beams are represented with bold line and dark blue color. The less necessary beams with less dark blue colors and unnecessary beam without change in their thickness (Figure 3), [23]. Extension to multi-objective optimization has been tried by Stavroulakis et al. (2008, 2009) [24, 25]. This approach is, historically, the first method of topology optimization.

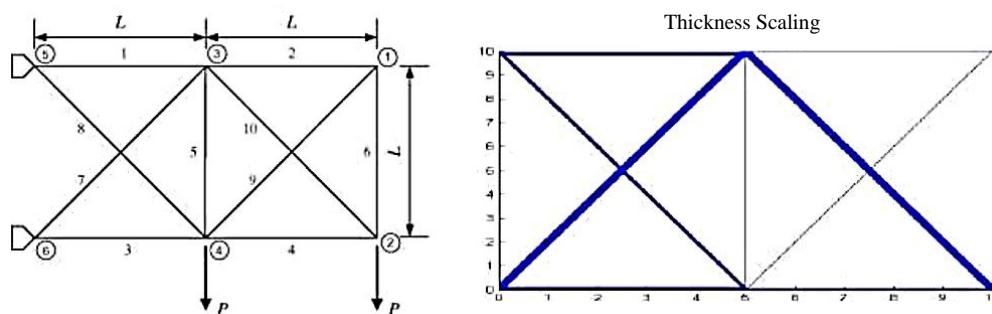


Figure 3. The design domain and the TO study results

### 2.1.2. Volume Based TO Method

The Volume-based is known as SIMP “Solid Isotropic Material with Penalization” method and is widespread in CAE software. The process starts by defining a linear block of voxels. Density of each voxel is defined between zero to one. If the value is equal to one then in this specific voxel the material is completely dense. If it is zero then in this voxel there is no need for material. Any other value indicates that material in this voxel has not to be solid for the enforced loads. These values are very useful in FEA models for topology optimization analysis [26]. In figure 4 is presented a typical topology optimization volume based problem [27].



Figure 4. Typical optimization problem

### 3. Results and Discussion

#### 3.1. 3D Modeling and Printing

Initially, in the results of the present study included the design and 3d printing of two types of furniture, a table and a chair (Figure 5). From each furniture three specimens with different inner wall thickness are printed. The specimens inner wall thickness is 10, 15 and 20 mm and the printing scale is 10% for chairs and 15% for tables. After the printing process has been completed, the post process stage follows, where the models are being cleaned up from the additional powder and immersed with hardener (Figure 6).

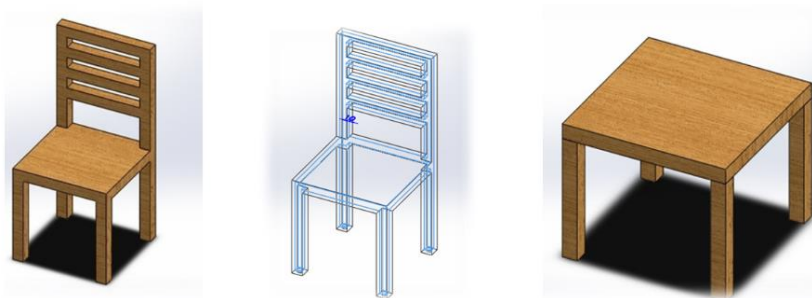


Figure 5. Table and chair 3D models with different wall thickness

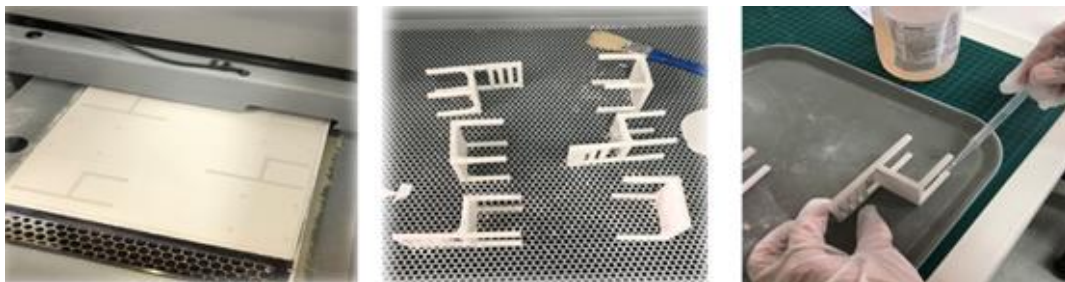


Figure 6. Printing and post processing Process

#### 3.2. Compression Tests Results

All six specimens have been tested in a compression tester. The moving speed of engine piston is 2mm/min. The specimens are kept at the center of crosshead so to be uniformly compressed (Figure 7). From the results (Table 1) we observe that between chairs the specimens 'chair\_10' and 'chair\_20' are hold out the highest load. However, until specimen 'chair\_10' to break piston covered the least distance. In addition, the 'chair\_10' has higher elasticity than the other two specimens until to break. The specimen 'chair\_15' hold out the lowest load, so is less durable than the other two. Also the piston take the same in 'chair\_15' and 'chair\_20' until to stop, but in 'chair\_20' the piston moves almost twice distance until to stop. A general conclusion is that the third chair is more durable than the other two. According to the piston distance, there is big difference between 'chair\_20' and the others specimens.

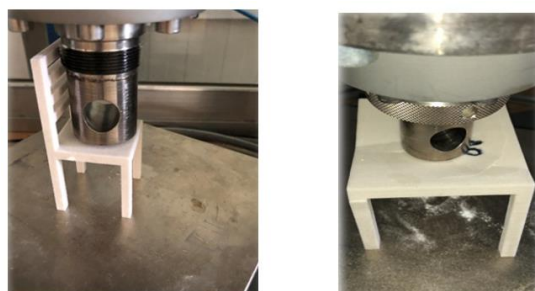


Figure 7. Specimens Compression Tests

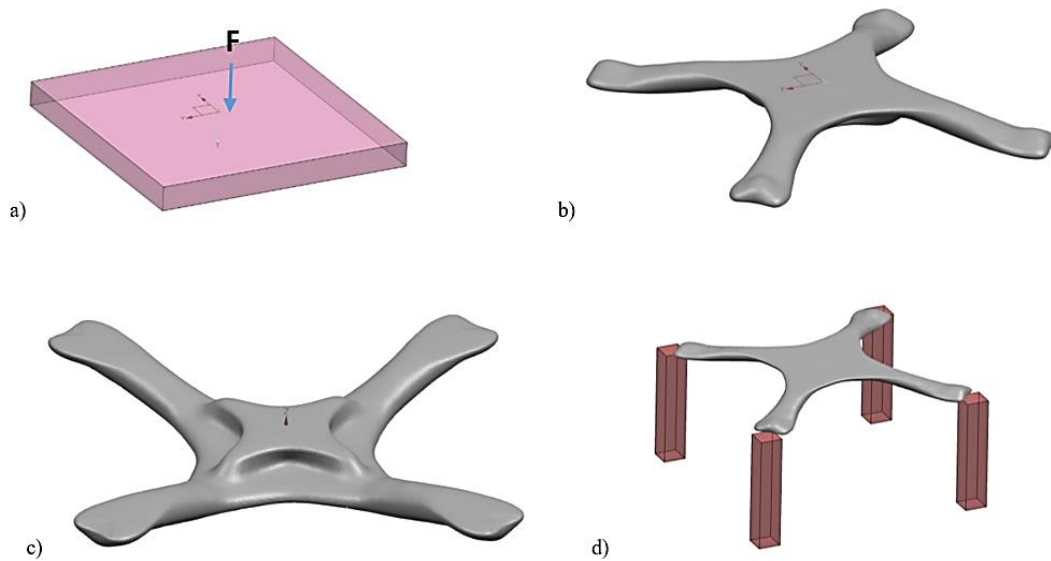
**Table 1. Compression tests results**

Specimen thickness (mm)	Force (N)	Piston Time to stop (s)	Piston Distance (mm)
Chair 10	216	14	0.5
Chair 15	188	15	0.6
Chair 20	216	15	1.1
Table 10	84	38	1.3
Table 15	156	36	1.2
Table 20	244	25	1.5

For table specimens, the 'table\_10' hold out the lowest load, but piston take more time to stop that the other specimens, this shows that it has great elastic behavior. The specimen 'table\_15' hold out double force than 'table\_10' but lower than 'table\_20'. The specimen 'table\_20' hold out the highest load force, but has the lowest into piston time to stop.

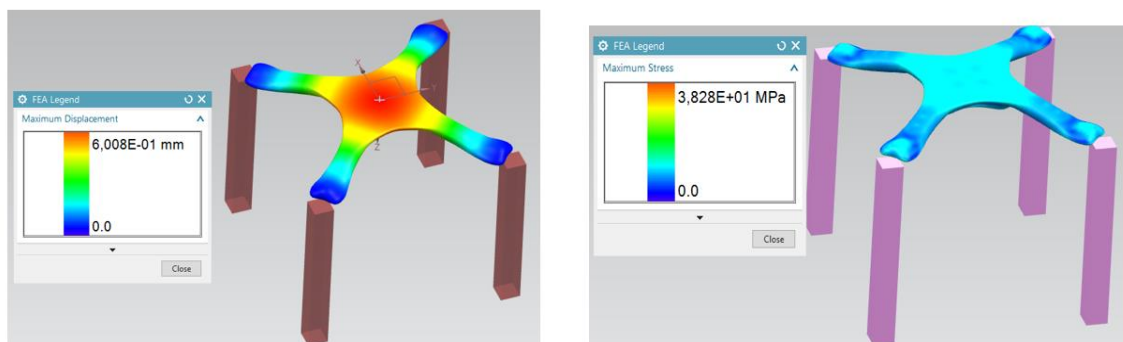
### 3.3. Topology Optimization (TO) Study

Afterwards, based on the tests results, a digital study for the table model is created, and the first TO study is performed. Topology optimization executed in Siemens NX software. The material in TO study has similar properties as powder in Z-450 printer [28]. According to the optimization scenario table legs shape and size remain the same and the upper table surface design will be optimized. As design space determined the whole model but only the upper surface is defined as 'keep in'. The selected design constrains are a) *Void Fill* and b) *Material Spreading in 35%*. The load case is the same as in compression test results, the upper table surface forced with 244N. From the results of this first study we see that table topology changes significantly (Figure 8).



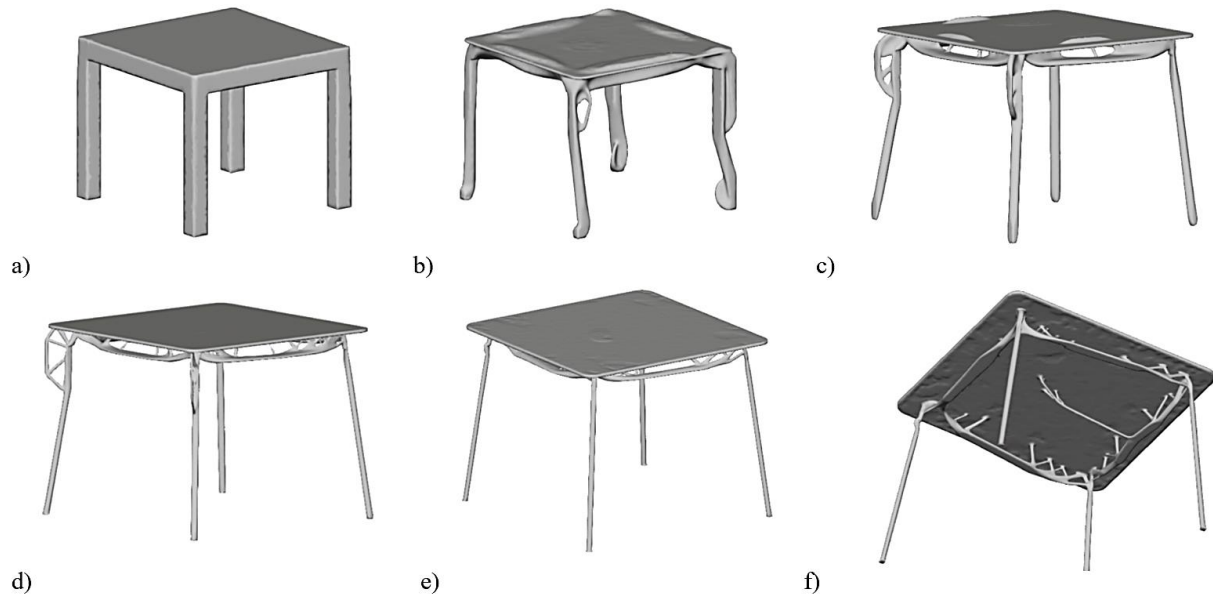
**Figure 8. a) The design domain; b) and c) The new topology optimized model, all constrains are satisfied; d) New models fits on design domain space**

In optimized model all constrains are satisfied and the model volume is reduced about 86 % and the the optimized model is stiffer than before (Figure 9).



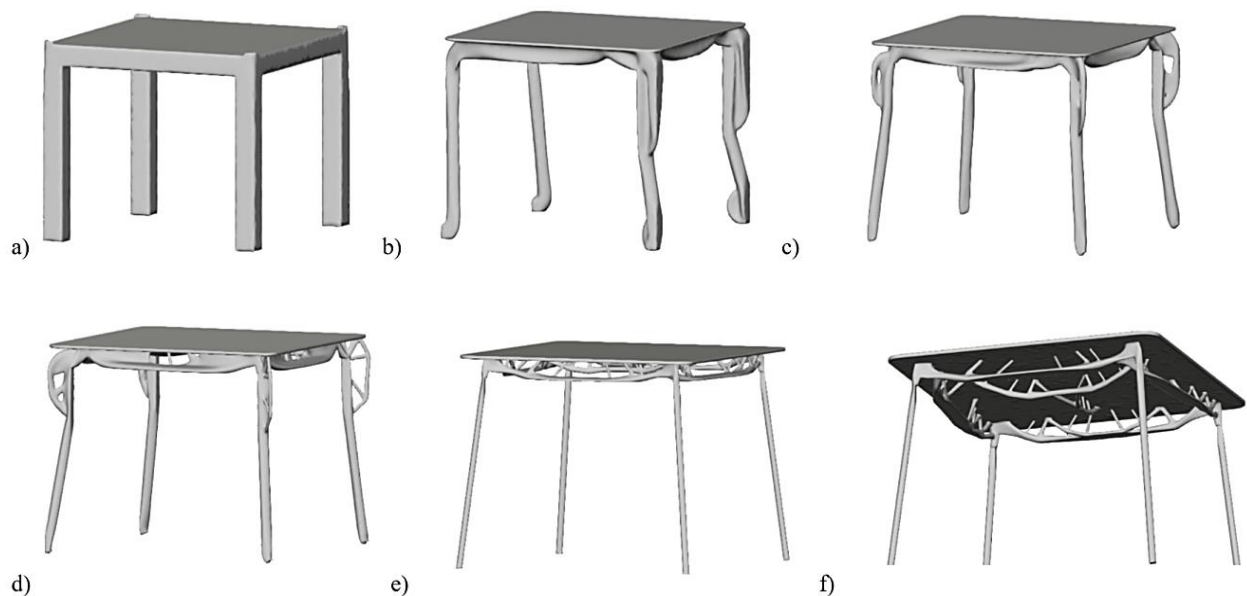
**Figure 9. The Maximum Displacement and Maximum Stress of optimized model**

From the above initial results, one observes that the shape of the optimized model obtain a geometry which is not predictable. The optimized model durability has increased and model mass has reduced. However, the top surface of the model is not kept flat throughout the length and width of the table. In the following TO study there are some differences from the previous. Initially, the upper surface of the table is defined as flat with a certain thickness. In addition, the legs of the table do not retain the initial shape but will be optimized. Furthermore, except the vertical force (244 N), small horizontal forces (30 N each) have been added on the right and on the left of table surface. In order to achieve more predictable results, additional constrains have been added (Figure 10). Mainly concerned with design space which remain empty of material such as the space between the legs. The results of the new study are more realistic. The density of the optimized model has changed significantly and the design constraints satisfied. The whole model geometry is acceptable and can be produced using an additive manufacturing technique.



**Figure 10. Material distribution during TO process.** The algorithm starts from the initial model geometry (a) after 45 iterations the model\_1 get the final optimized geometry (f), the intermediate model shapes are shown from (b) to (e).

Although the optimized model (Figure 10) is robust enough some problems remain and need to be solved. Specifically, above the upper surface of the table there is material concentration. This amount of material act as ribs and thus affect the density distribution in the rest of the model. Therefore, additional constraints should be defined to the upper surface of the table so that to be flat. Particularly, this constraint ensures that the material distribution will not overcome the upper surface. After adding the new constraint, the material distribution throughout the optimized model has changed (Figure 11).



**Figure 11. Material distribution changed.** The algorithm starts from the initial model geometry (a) after 42 iterations the model\_2 get the final optimized geometry (f), the intermediate model shapes are shown from (b) to (e).

### 3.3.1. Optimized models Finite Element Analysis (FEA)

In this section we are going to present the executed FEA studies for the topology optimized 3d models. In the first study the load case is based to experimental results. The results of the first study are presented in Figure 12.

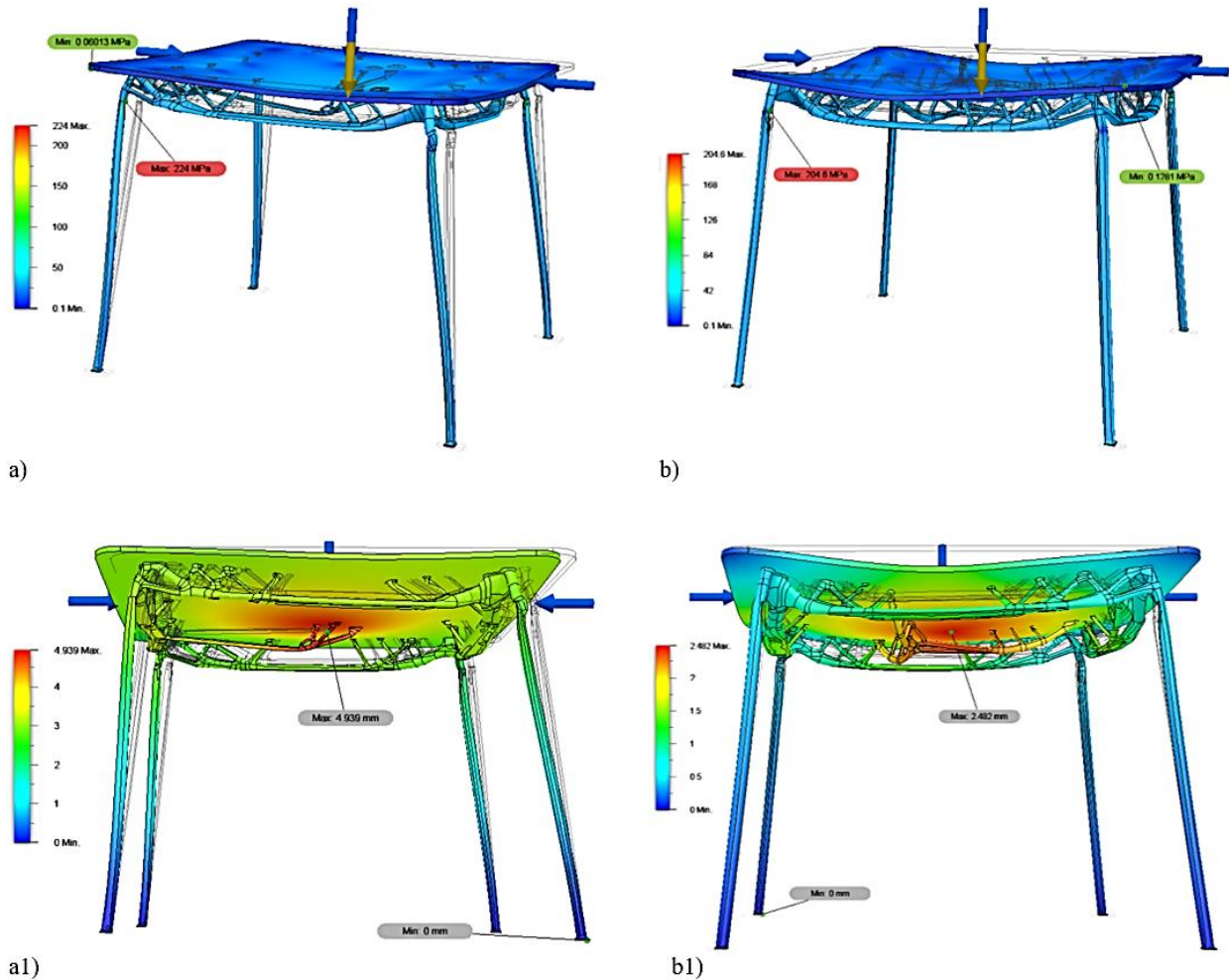


Figure 12. First FE analysis, the vertical force is 250 N and the horizontal forces are 30N each one. a) Von Misses Stress and; a1) Total displacement of the model\_1; b) Von Misses Stress and; b1) Total displacement of the model\_2.

From the above results the model\_1 (a) deformed permanently and fractured. In the model\_2 the maximum stress is 10% less than the first model and deformed permanently. The total displacement in model\_2 (b1) is 50% less than in the first model (a1). In general, model\_2 is stiffer than model\_1 but, in both models the weakest domain is the area where the legs start. Afterwards, we are going to perform two more FE analysis with lower vertical force. In first study the vertical force is 200N and in the second is 150N, the horizontal forces are 30N. The results from all three FE analysis are presented in Table 2.

The results of the finite element study lead to redesign parts of the models in order to improve their strength and to create a symmetrical model. We select to redesign legs because their geometry is not symmetrical and during the FE analysis they are fractured or they deformed permanently. The new legs geometry has homogenized structure and symmetrical shape (Figure 13).

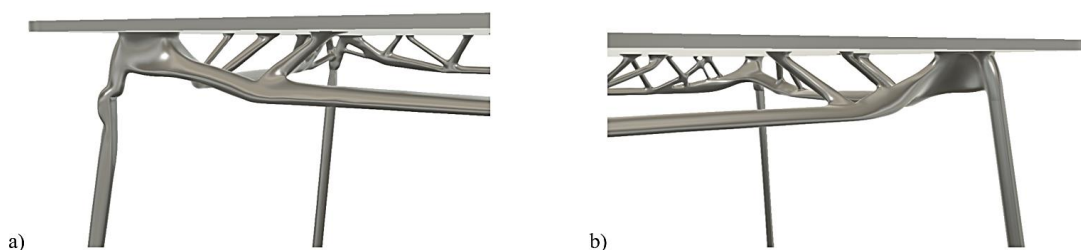
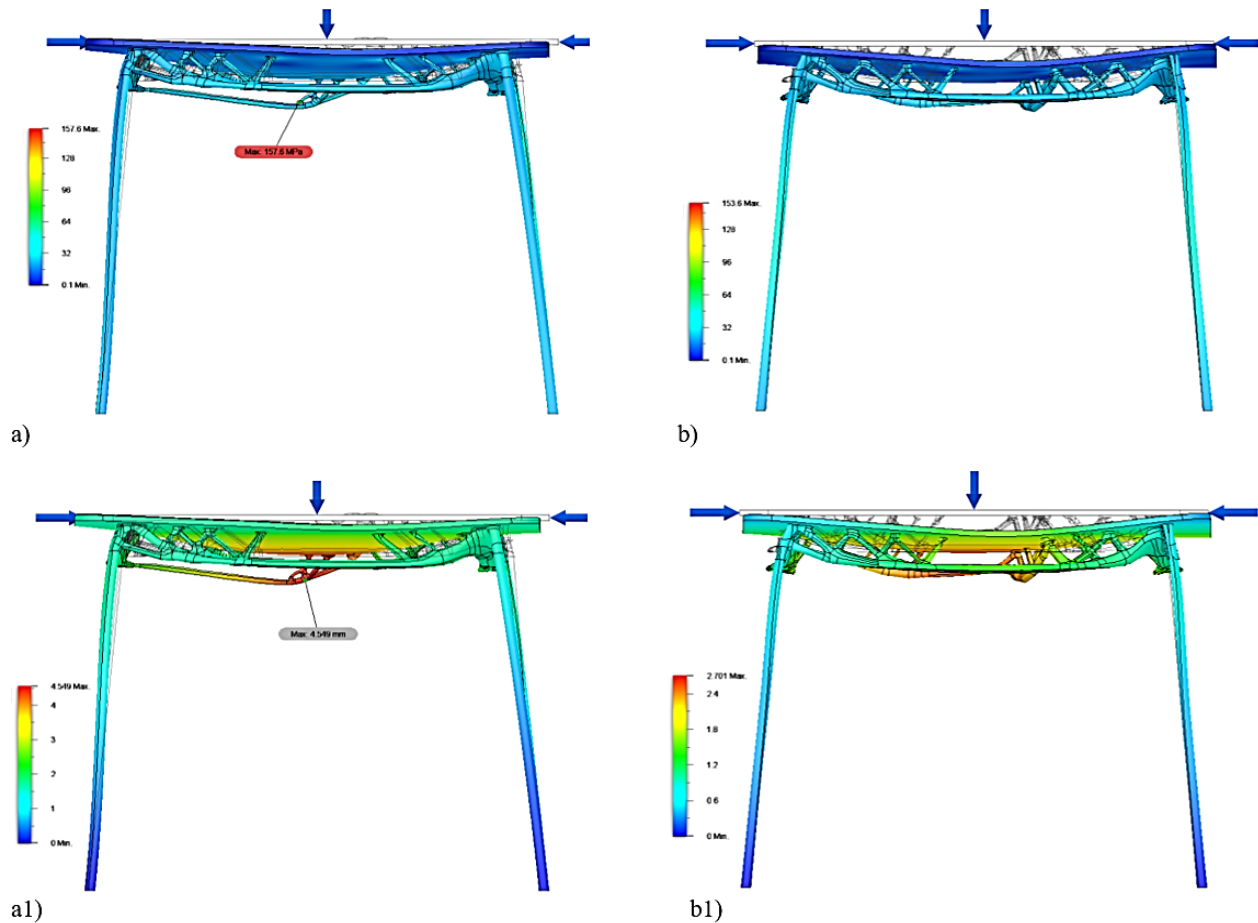


Figure 13. a) After TO study each leg had different and non-uniform shape b) After redesign process legs has a more durable, uniform and symmetrical shape

In order to check the stability of the redesigned models three FE analysis are performed. The loads and constraints are the same as in the previous studies. In the worst case scenario of 250N vertical force the behavior of two models is better. The total Von Misses stress is reduced and models are more durable. In total displacement there aren't significant changes (Figure 14).



**Figure 14.** After redesign process models have a better behavior in FE analysis. a) The maximum Von Misses stress in model\_1 is lower than the initial model, especially in legs the stress is up to 70 MPa; a1) The total displacement of model\_1; b) The maximum Von Misses stress in model\_2 reduced about 80 MPa; b1) The total displacement of model\_2.

Useful results emerge from the above finite element studies. Observing the numerical results of the studies we see that there is a logical sequence in the results which means that the Finite Element Analysis is defined correctly (Table 2). In addition, the redesign process contributed significantly to improving the durability of 3D models by reducing model stress. In addition, the redesigned areas now receive significantly less load. Possibly, further redesign of the model structure would lead to even better static behavior of the models.

**Table 2. Results of all six Finite Element Analysis**

Study	Model	Force (N)	Max Stress Von Misses (MPa)	Total Displacement (mm)
TO models Study_1	Model_1	250	224	4.94
	Model_2	250	204	2.48
TO models Study_2	Model_1	200	179	3.95
	Model_2	200	163	1.98
TO models Study_3	Model_1	150	134	2.97
	Model_2	150	123	1.49
Redesigned models study_1	Model_1	250	157	4.54
	Model_2	250	153	2.7
Redesigned models study_2	Model_1	200	126	3.64
	Model_2	200	122	2.16
Redesigned models study_3	Model_1	150	94	2.73
	Model_2	150	92	1.62

## 4. Conclusion

From the beginning of the 20th century until today, the product design process changed drastically. In the last decade, a well-established design process has consisted of three general phases: a) learn, b) design, and c) prototype. In this article, we focus on the prototype stage, which includes: a) creating prototypes to help designers evaluate an idea; b) creating prototypes, which users will test. For both reasons, a fast, cheap, and accurate way to create prototypes is the use of 3D printing and Additive Manufacturing (AM) techniques. In this study, we used the Inject Binder technique to create the prototypes. In total, six specimens, three chairs and three tables with different wall thicknesses, are printed and tested in a compression tester device. The results show that the hollow specimens are durable enough and it is not necessary to be solid. In the next stage, the experimental results are used in order to perform Topology Optimization studies for the table model. From the TO studies, complex 3D models are created that are difficult or impossible to produce with traditional manufacturing methods. In most cases, AM is the appropriate method to manufacture topology optimized models. The first TO study refers only to the table surface, but the other studies are performed on the whole model. In order to check the durability and stability of optimized models, Finite Element Analysis is performed. The results show that the structure of table legs is not homogenous and the model fractured. Afterwards, there follows a redesign process in which the legs obtain a symmetrical and homogenous structure. The new FE analysis shows that model redesign has led to a stable structure and Von Mises stresses have been reduced significantly. Evaluating the results, we come to the conclusion that the proposed methodology is correct and worked efficiently in order to create a topologically optimized and robust model. Future research should consider the potential effects of Topology Optimization in the product design process in combination with Additive Manufacturing.

## 5. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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