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Research Article

Structural and topology optimization of steel construction profiles in solar energy systems

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Abstract: In recent years, significant investments have been made for Solar Power Plant (SPP) plants in many countries. The installation costs of SPP plants are quite high. This situation increases the amortization period of investments. Lowering these costs during the installation phase will pave the way for more investments. One of the most important cost items of SPP is steel construction costs. In this study, we aim it to reduce the cost by designing the best performance product by reducing the weight of C profiles, one of the steel constructions used during the installation of solar panels, with shape and topology methods. The calculated weight gain for the optimized model was 7,732 kg, derived from the difference between the initial weight of 60,800 kg/m and the optimized weight of 53,068 kg/m. This represents a percentage gain of 12.717%. The results got show that shape and topological optimization can provide significant gains in terms of cost.

Keywords: Solar Energy Systems, Structural and Topology Optimization, Steel Construction Profiles, Weight Reduction, Manufacturing Engineering

1. Intorduction

With the advancement of production technologies in the manufacturing sector, the product design stages have become crucial in reducing the weight of elements affecting material selection and total weight without compromising the product's functionality. This is significant not only from a cost perspective for manufacturers but also in providing ergonomic usage for end-users and making substantial contributions to the ecosystem.

In recent times, with the widespread adoption of solar energy facilities, reducing installation costs has become a critical focus area. Factors like angle, height, wind speed, precipitation in winter, and surface contamination affect the manufacturing of solar energy facilities. Manufacturers, aware of the potential cost increase, strive to address this through various methods and techniques, such as optimization methods. Academic studies have showed the application of optimization methods in this context.

Yang and Chuang introduced the Density Method in 1993 [1]. Another method, the Homogenization Method, was proposed by Bendsoe and Kikuchi in 1998 [2]. The finite element solver Optistruct solves optimization problems using the known density method for material distribution [3]. They conducted tests on designed components to identify critical areas. They perform topology optimization to enhance fatigue life [4]. Reducing the weight of parts in vehicles will contribute to reducing the total vehicle weight. Reducing vehicle total weight is a critical parameter for structural engineering applications that reduce fuel consumption [5]. Furthermore, the determination of areas to be emptied with different geometric shapes on a part is significant, considering their relationship with other assembled components. Therefore, the location of critical stress points is vital, enabling the determination and optimization of motor, suspension, transmission, and other component mounting locations [4, 6, 7].

In order to get high-strength materials without changing the dimensions of the product to be optimized, they extract the areas are extracted from specific regions, saving time and providing a lower-cost and faster solution. Solidworks® Simulation program is used for topology optimization to achieve this [8]. The aim of topology optimization is to find the most suitable material distribution that maximizes rigidity [9].

Today, more advanced techniques are used, and it can apply finite element methods to complex problems. Optimization is a tool used to maximize the benefit of a structure under a specific aim. In structural optimization, the "best structural design" is selected in three categories: Size Optimization, Shape Optimization, and Topology

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Optimization. Topology optimization aims to find the best material distribution in a given structure, primarily managed because of weight savings. There are many applications [10, 11 12]. While shape and size optimization methods are intriguing, topology optimization focuses on optimizing the thickness and boundaries of parts to get a design that maximizes the use of the entire geometry area [13]. Structural topology optimization aims to prevent the use of unnecessary material and to create a structure that will best transfer loads to supports. It is used to get a system structure that meets design constraints as effectively as possible. Thus, topology optimization aims to create a structure with the minimum weight of the part and maximum strength [14].

Topology optimization seeks the most suitable configuration for structural optimization [15]. Using solid modeling and finite element analysis of these models in a computer environment reduces the cost of previous designs and significantly reduces the number of tests. The analysis of the tram's crash attenuating structure resulted in a lightweight design [16].

Topology optimization, which allows for the design of lightweight parts by distributing materials appropriately while maintaining the part's function in manufacturing technologies, is an effective method in the manufacturing sector [17].

In this comprehensive study, the weight of C-profiles, integral to steel constructions for solar panel installations, underwent optimization through shape and topology methods, with the dual objectives of enhancing performance and minimizing costs. The rigorous application of shape optimization involved refining geometric configurations for optimal load distribution, while topology optimization strategically redistributed material to improve mechanical properties and reduce unnecessary weight. The outcomes revealed a significant effectiveness in achieving these goals, showcasing superior performance metrics in the optimized C-profile designs. Beyond structural enhancements, the resultant weight reduction not only contributes to increased efficiency but also aligns with the broader aim of cost-effectiveness in solar panel installations. This research not only advances the understanding of optimizing steel constructions for renewable energy infrastructure, but also lays the groundwork for future innovations in the field, emphasizing the role of innovative engineering in fostering sustainability and economic viability.

2. Material and Method

In this study, we have targeted the optimization of the final product using shape, structural, and topology methods. The optimization objectives are shown in Figure 1. The initial problems are shown at left hand side and the optimal solutions are shown at the right-hand side. To examine structural and topological optimization for the optimization objectives, it is necessary.

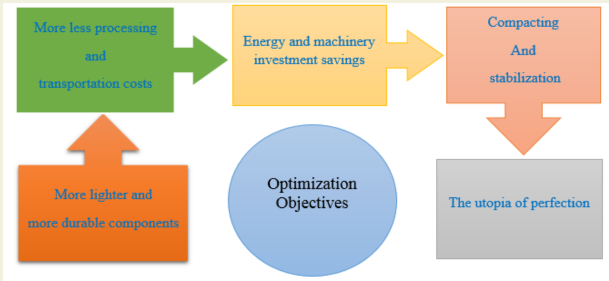

Figure 1. Optimization Objectives [18]

2.1. Structural Optimization

As shown in Figure 2, Structural Optimization encompasses various optimization types, including size, shape, topology, and topography optimization. Size optimization focuses on optimizing the profiles in the design, shape optimization targets the optimal designs for radii and holes, topology optimization aims to achieve the most suitable material distribution within the design volume, and topography optimization is used to get the best designs on sheet metal plates.

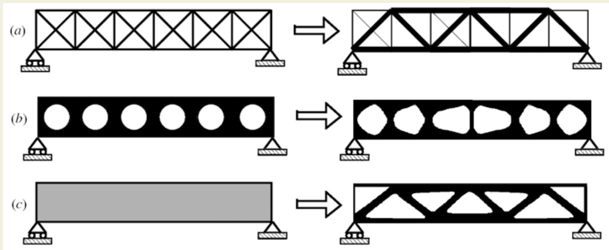

Figure 2. Structural Optimization, a) Sizing optimisation, b) Shape and c) Topology optimisation[10].

2.2. Topology Optimization

Under the specified constraints and objectives, achieving the most suitable material distribution, getting the best design, and creating high-quality and high-performance products are the preferred optimization method in the additive manufacturing sectors.

When establishing the optimization implementation processes, they conducted the analyses based on predetermined objectives to determine the steps to be taken, the techniques and methods to be used, and the materials to be developed in line with the defined goals.

2.3. Optimization and Optimization Processes

The process of creating the best-performing product by subjecting the existing product to forces under certain conditions, after determining the sensitivity of the lower and upper constraints, with a focus on reducing both material selection and total mass before delivering the product to the user.

Optimization can contribute in three ways: contributions to manufacturers, contributions to users, and contributions to the environment.

Through optimization, selecting the right materials for research and development activities, reducing the total weight through light weighting efforts, and contributing to the lifespan of machines used in manufacturing technologies can provide advantages to manufacturers from a cost perspective. The performance product got through optimization can offer comfort to the end user. The optimized design product, by influencing the correct processing of resources and reducing the emission of toxic gases into the environment, contributes to the preservation of the natural environment.

2.3.1 Creation of Content

They showed the general stages of content creation in Figure 4. While determining our content; we examined scientific articles on weight reduction. In the articles reviewed, experience gained in how optimization studies were created using shape, structural and topology methods. In line with these, we have transferred solar panels to the optimum designs of the constructions.

In this study, we have developed an optimal process to reduce the steel construction installation costs of SPP. We give these process stages given in Figure 3.

2.3.2 Material Development

In this study, we have designed 52 models created with galvanized steel material in three dimensions using Solidworks solid modeling software. In each of the 4 C-profiles in the models, we used 20 circular geometric shapes for hollowing, with the condition that their positions remained fixed. This resulted in 80 circular forms across the 4 C-profiles. Starting with a minimum diameter of 1mm, the diameter increased incrementally, reaching a maximum diameter of 99 mm in each case, aiming to reduce the total weight. Each time, a total force of 1920 N applied, and the physical behavior of the C-profiles under force analyzed using the Solidworks Simulation program and illustrated with graphs.

2.3.3 Modeling and Analysis in Optimization

Using software in manufacturing technologies provides designers with multiple options. As technology advances, designers can create innovative designs. They can analyze the created models with simulation software, and it can document multiple analysis results of the product in reports. By examining the analysis results, the designer can identify and review any errors compared to reference models gained through experience. Afterward, necessary interventions can be made to design variables to improve the final performance product. It showed the Optimization Algorithm used in product development in Figure 5. We can group optimization terms under four headings: constraints, design variables, optimization area, and performance product determination.

2.3.3.1 Constraints

The models to be subjected to analysis are considered under specific loads and constraints, with the reference models being the models without any constraints, i.e., the initial version of the model, the model with lower constraints, and the model with upper constraints. The ability of other design variables to respond to these reference models is then evaluated. In the model with lower constraints, the smallest diameter circular sections (Q=1 mm) to be removed from the areas subjected to optimization are shown in Figure 6. In the model with upper constraints, the smallest diameter circular sections to be removed from the areas subjected to optimization (Q=99 mm) are shown in Figure 7.

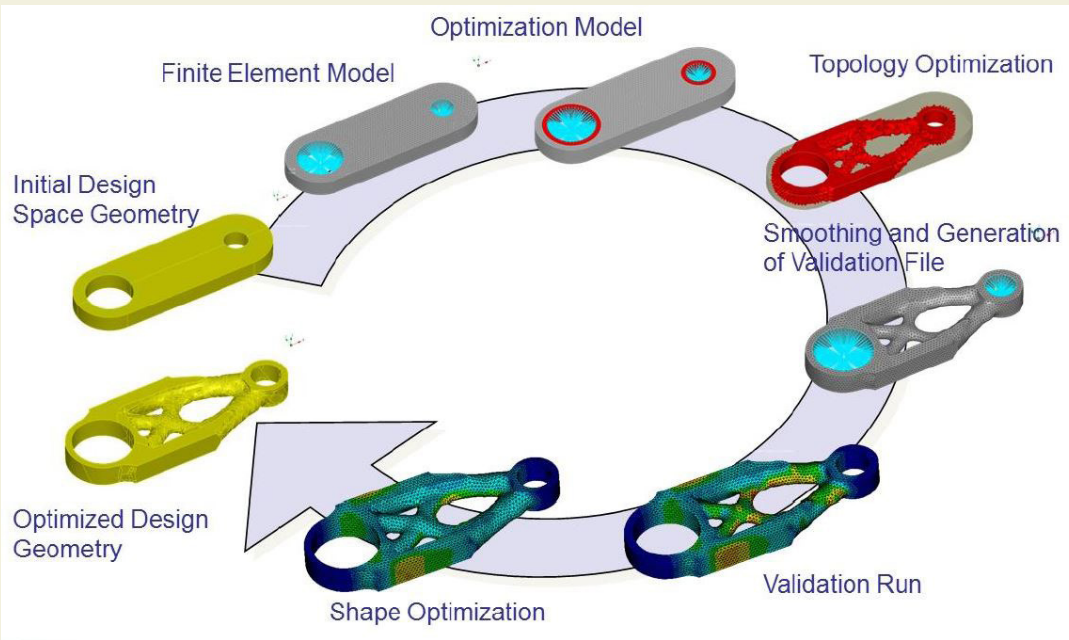

Figure 3. Design Stages in the Topology Optimization Process [7]

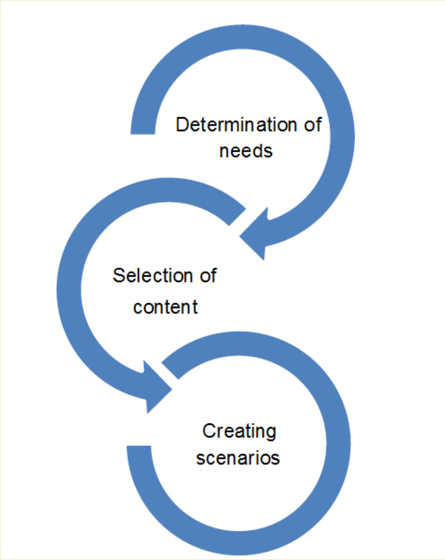

Figure 4. Creating Content [7]

2.3.3.2 Design Variables

Design variables are parameters that can be modified beyond the material selection or fixed loads, different from the reference models. In the case of solar panels, the material used is galvanized steel, and the variable parameters are the diameters of the circular cutouts in the C-profiles. Apart from the models with lower and upper constraints, the circular sections to be removed from the areas subjected to optimization range from a diameter of (Q=2 mm) to a diameter of (Q=98 mm).

2.3.3.3 Optimization Area

The areas where topology optimization will be applied based on changing parameters, excluding the boundaries that the design cannot respond to, are the optimization areas. These areas are shown in Figure 8.

2.3.3.4 Determination of Performance Product

The manufacturer can optimize the production technologies to obtain the best product, also known as the optimal product or performance product that can provide the desired response to the manufacturer, user, and the environment based on the analysis results while considering the comfort desired by the user.

2.3.3.5 Objective Function

It is expressed as the ultimate goal of the optimization process. For example, it can provide advantages such as user comfort, cost advantage for the manufacturer, and environmental friendliness. It is defined as f(*x*); the objective function. The type of the objective function depends on the nature of the problem.

Details of the processing stages of the selected sample part are shown in Figure 9.

2.3.3.6 Application of the Method

A general optimization problem can be defined as making an $f(x)$ function, dependent on the variable x and subject to constraints, as small or as large as possible [19].

Where x represents a design vector consisting of a series of variables in the design process, known as an n-dimensional vector. f(*x*) is defined as the objective function.

Shown in Equations (1) and (2) and represent inequality and equality constraints, respectively. These design constraints are the requirements that must be met to obtain an acceptable design. In a general Topology Optimiza-

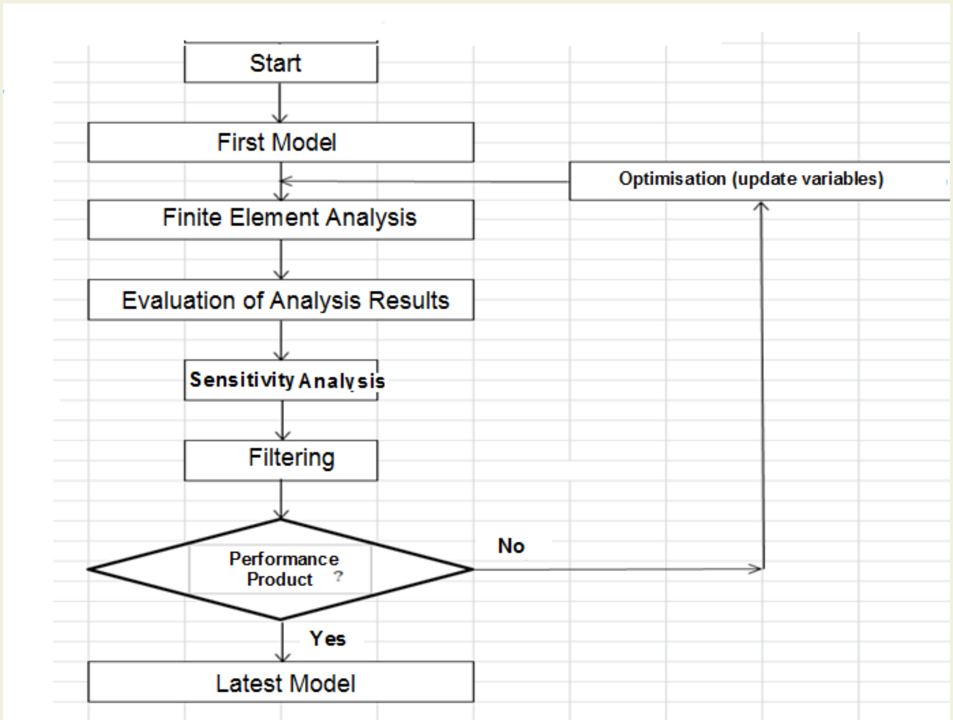

Figure 5. Optimization Algorithm

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tion problem statement, for each finite element produced during the network generation phase (i), a design variable (ηi) is assigned, which is an internal pseudo-density of the model. The pseudo-density ranges from "0" to "1", where $\eta i = 0$ represents material to be removed from the design, and $\eta i = 1$ represents material to be retained in the design [19].

Figure 6. Lower Constraint Will Apply "Model-Q-1"

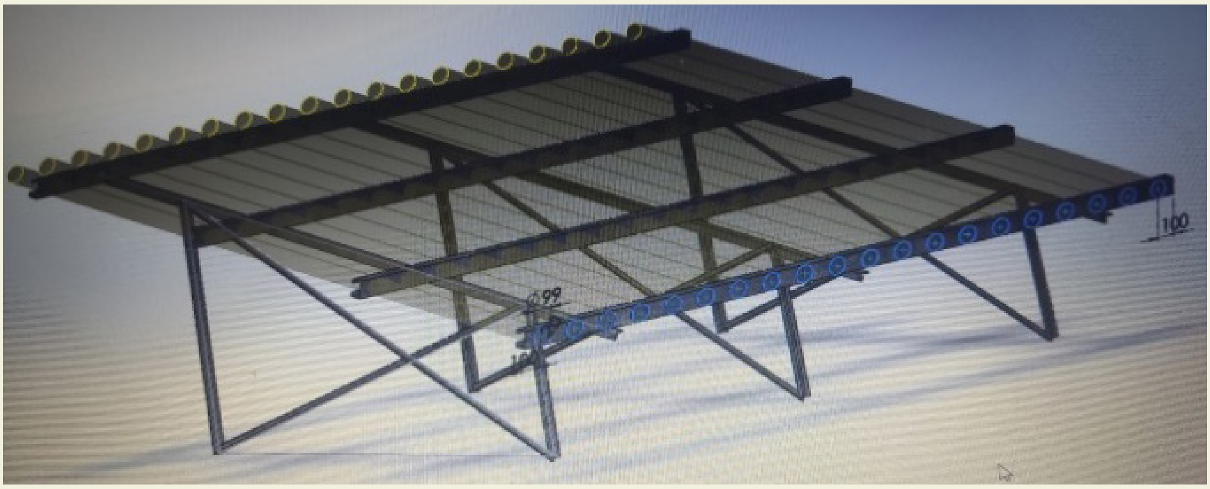

Figure 7. Upper Restriction Will Apply "Model-Q-99"

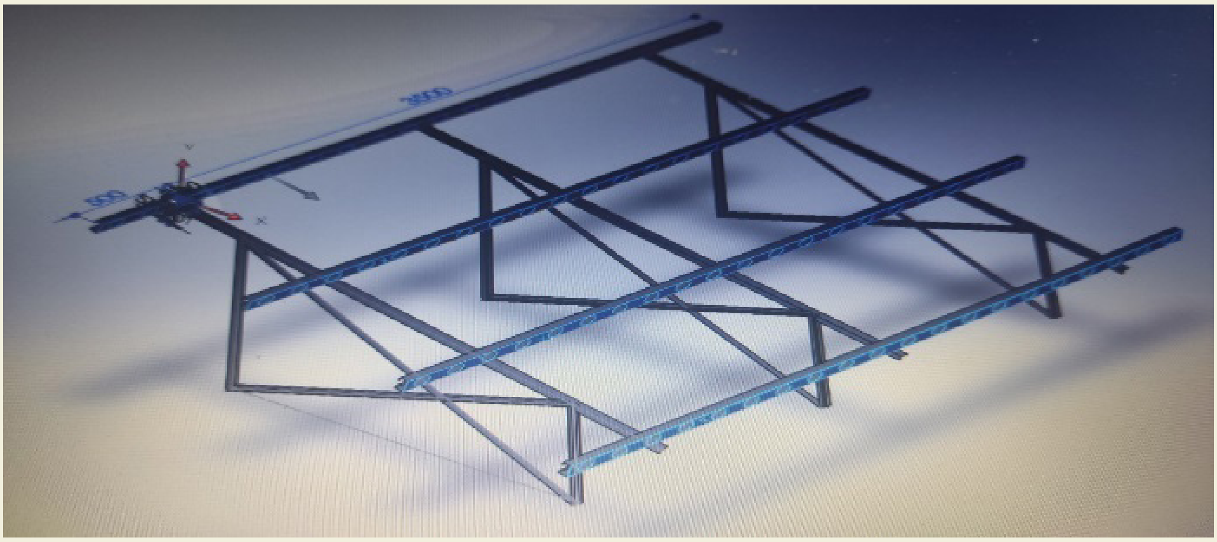

Figure 8. Areas to be subjected to optimisation in the models

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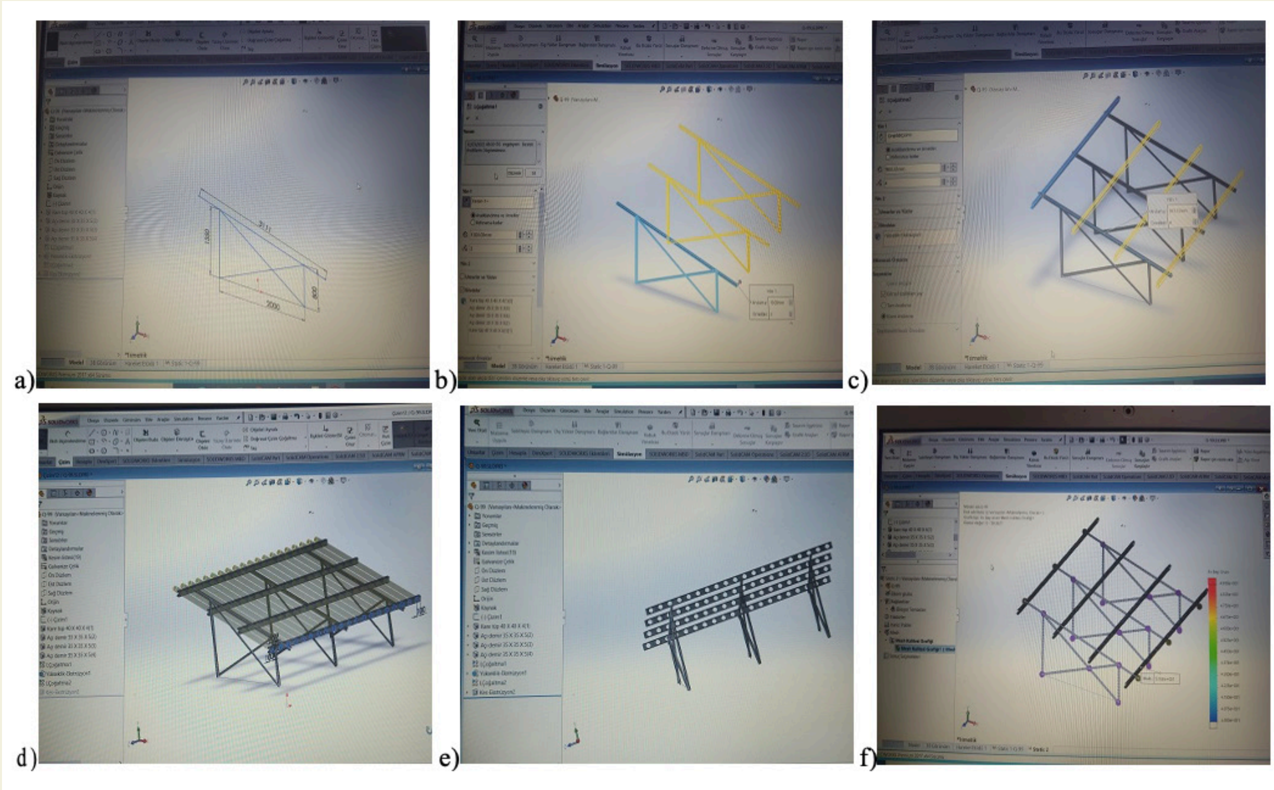

Figure 9. Selected sample part Selected sample part; a) Drawing the bottom profiles, b) Creating the bottom profiles, c) Placing the C profiles, d) Determination of the areas to be emptied from C profiles, e) Emptied version of the design, f) Creating the mesh structure of the design.

$$1 < g_j(x) < 100 \qquad j = 2,4,6,\ldots,99,9 \tag{1}$$

upper restriction diameter (Q=99mm) was taken.

$$1 < l_j(x) =< 100 \qquad j = 0.1, 0.2, \ldots, 1 \tag{2}$$

$l_j(x)$ lower restriction diameter (Q=1mm) shown in equation (3) was taken.

$$l_j(x) = 0 \qquad j = 0 \tag{3}$$

The initial diameter of the model (Q = 0 mm) was taken.

The Topology Optimization method can also be expressed as follows:

$f(\eta_i)$ function is the smallest / is about to become the greatest value of making,

$$1 < \eta_i(x) < 1 \quad i = 1,2,4,6,\ldots,N; \; g_{aj} < g_j < g_{uj}$$

$$j = 1,2,3,4,\ldots,M \tag{4}$$

In the equations (4); N = number of finite elements, M = number of constraints, g_j = calculated constraint value g_{aj} and g_{uj} = are defined as lower and upper constraint limits [19].

2.3.3.7 Perspective Rear Views of Models with appling Lower Constraint

2.3.3.8 Finite Element Analysis

Finite Element Method, helps the designer to form an idea about the behavior of the model formed by the combination of all the parts that make up the design, against certain forces and strains, before production.

Meshing

It is a critical step for the analysis of models. The length, tolerance and on-site mesh control of the part ensure that the features of the product to be produced in the process of production technologies are shown in detail in the technical specifications. Mesh control; It allows specifying different element sizes for nodes, vertices, surfaces, and edges [20].

3. Results and Discussion

3.1. Profiles' Weight and Cost Calculations

A total of 52 CAD model designs were created in line with the content. The designed CAD models are subjected to finite element analysis in the Solidworks® Simulation program using a mixed curvature-based mesh structure. For each model in accordance with the prepared scenarios, results in the form of Static Node Stress, Static Tension, Static Displacement, and Safety Factors were obtained in graphical format. Table 1 below compiles the dimensions of solar panels commonly used in residential and commercial areas. The first noticeable aspect in the table with average measurements is the direct proportionality between the number of cells and panel dimensions. It can be observed that 72-cell panels are approximately 33 cm longer than 60-cell panels [21].

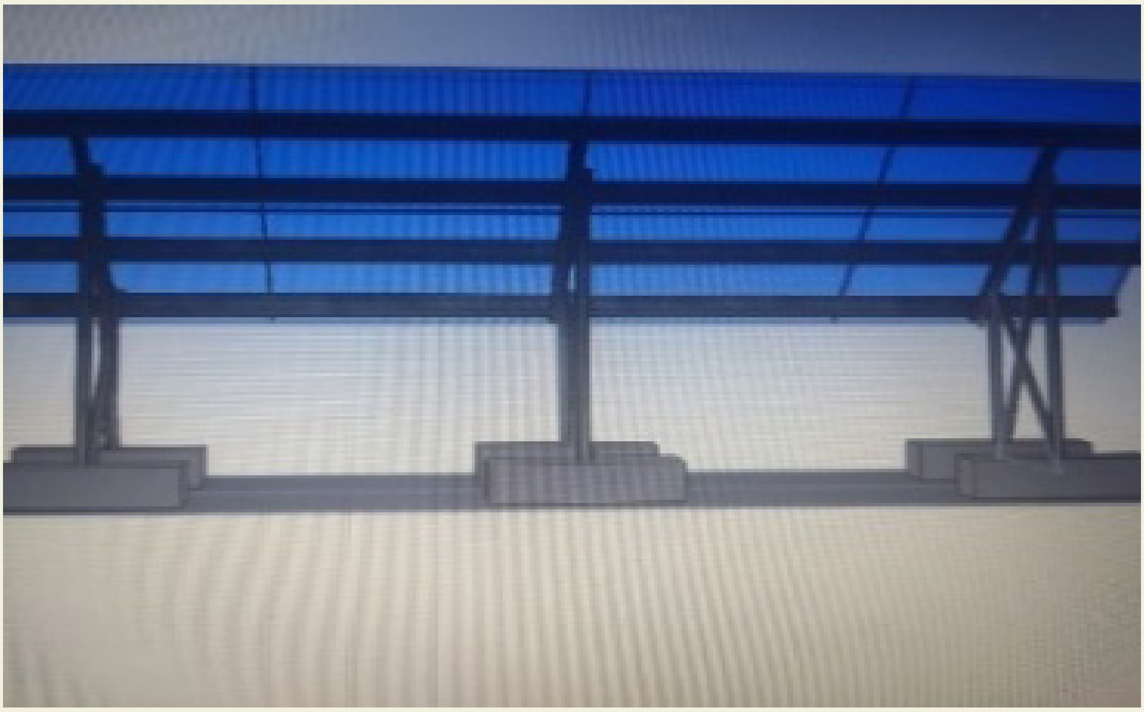

Figure 10. Model-Q-1

Figure 11. Model-Q-40

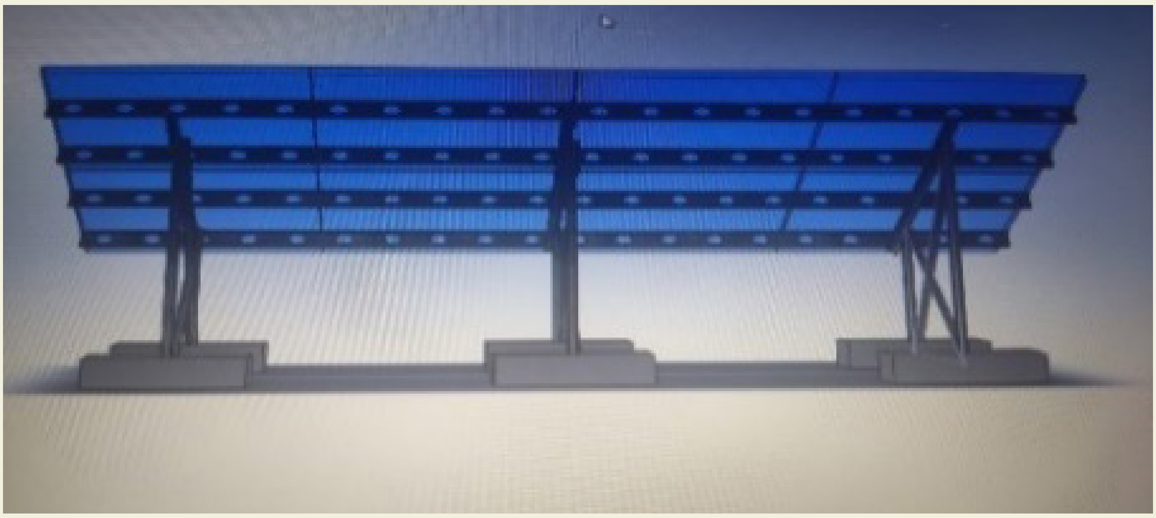

Figure 12. Model-Q-70

Table 1. Dimensions of solar panels used in residential and commercial areas [21].

Panel Properties	Residential	Commercial
Number of Cells	60	72
Average Height (cm)	165	198
Average Width (cm)	100	100
Average Thickness	3,5-5	3,5-5

Solar panel calculation for home; Approximately 20 panels are used for a 6kW system. The system to be installed will be approximately 8.5 meters wide and 4 metres long. In total, it will cover an area close to 33 square meters [21].

The weights of some panels are given in Table 2. While a panel with a power of 275 W weighs 20 kg, a panel with a power of 320 W weighs 19 kg [21].

Table 2. Weights of Solar Panels Used in Residential and Commercial Areas [21].

Brand	Watt	Type	Number of Cell	Weight (kg)
Elin Plus	320	Monocrystalline	60	19
Elin Plus	320	Monocrystalline	60	19
Alfasolar	275	Polycrystalline	60	20
Alfasolar	325	Monocrystalline	60	20
Jinko	405	Mono Perc	Half Cell-144	22,5
Elin Plus	395	Monocrystalline	72	22,5
Alfasolar	400	Monocrystalline	72	24

In this study, the dimensions of commercially installed solar energy panels are used. Dimensions, weights and properties of a panel used in the models;

Width=1000 mm, Length= 1980 mm, Brand=Alfasolar,

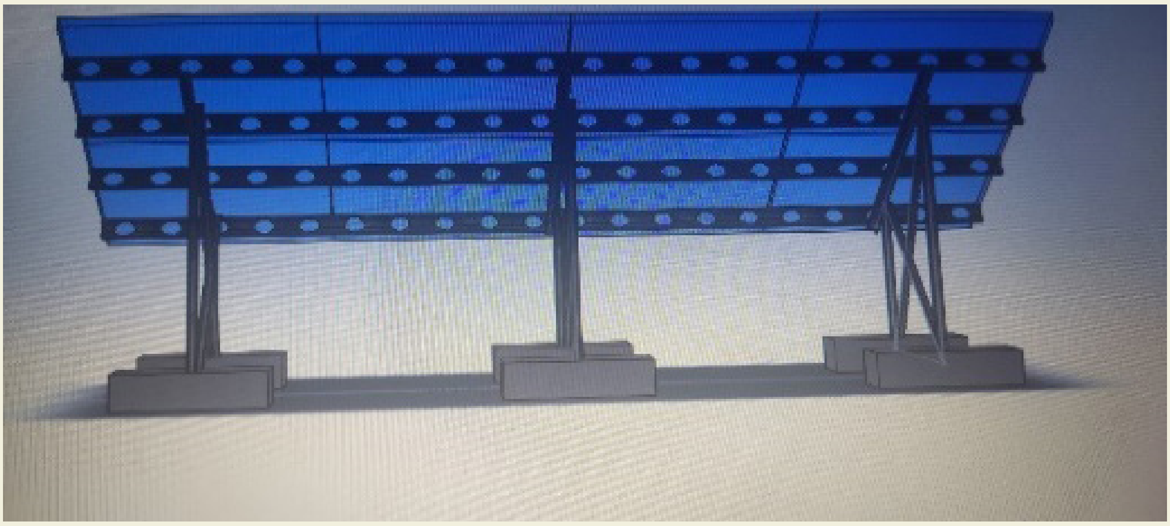

Figure 13. Model-Q-90

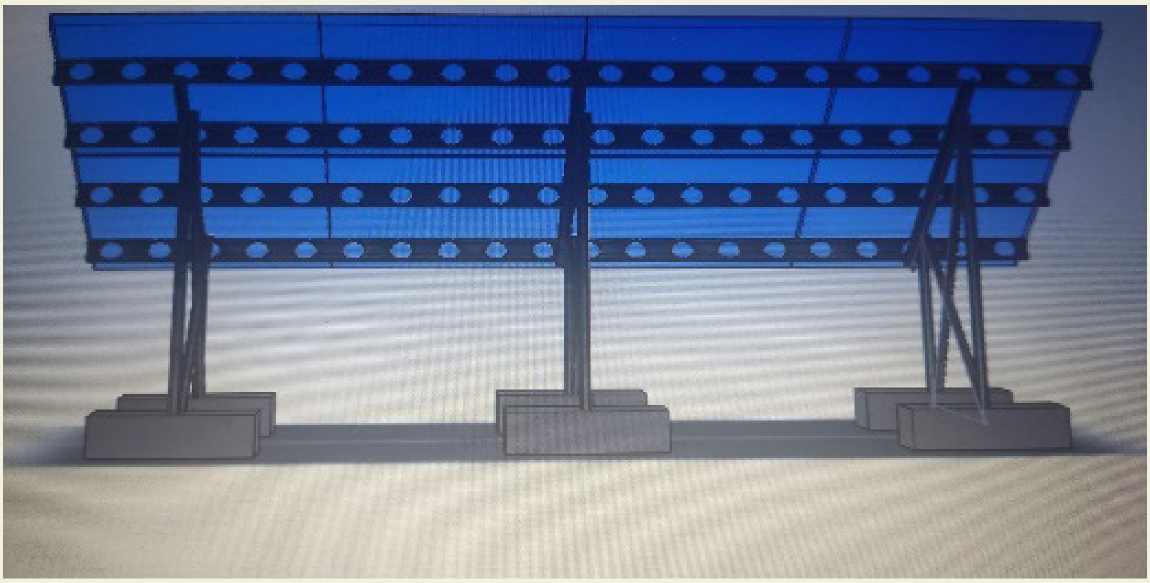

Figure 14. Model-Q-99

Type: Monocrystalline, Number of cells=72, Weight=24 kg, Total Weight = 24×8= 192 kg (Figure 15 and 16).

Force applied for analysis; 1 kg = 10 N

Applied force = (Total weight) × (Newton in kg) = 192 × (10 N) = 1920 N

3.2 C Profiles Weight Calculation

The properties of Profile C used in the model are given in Table 3. 20 circular forms will be cut from 1 C profile used in the model. A total of 80 circular forms will be cut from 4 C profiles used in the model (Figure 17 and 18).

In the proposed model, 4 C profiles were utilized with a total weight of 60,800 kg/m and a combined length of 16,000 mm, equivalent to 16 meters. Following optimization, the weight of the refined model (Figure 10-14), designated as "Model-Q-90," was determined to be 63,068 kg/m. Consequently, the calculated weight gain for the optimized model was 7,732 kg, derived from the difference between the initial weight of 60,800 kg/m and the optimized weight of 53,068 kg/m. This represents a percentage gain of 12.717%. The optimization process resulted in a notable improvement, enhancing the efficiency and performance of the model.

Table 3. Specifications of Profile C used in the model

Parameter	Specifications Values
Material Type	Dip galvanised steel
Size	4000 mm
Width	250 mm
Thickness	2 mm
Material Specific Gravity	7,6 gr. / cm^3
Size 1000 mm Weight of profile C	3,80 kg/m
Weight of 4000 mm C profile used	15,200 kg/m
Weight of 4 pieces of 4000 mm C profile used in the model	4×15,200 = 60,800 kg/m

3.3 Reduced Graph of Weights of Models

Proposed Model "Model-Q-90" Result Graph

Model-Q-90 static node stress, static strain, static displacement, and safety factor result graphs, along with the maximum and minimum values for each graph, are shown in Figure 19. As the diameters of the circles to be removed from the areas subjected to optimization in the C-profiles, one of the model components, increase, and the total weight of the model decreases. As the diameters of the circles to be removed from the areas subjected to

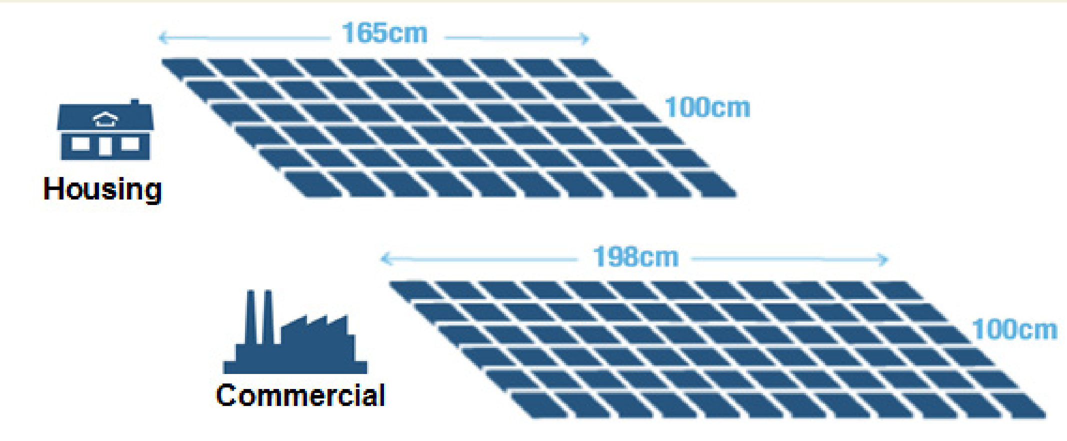

Figure 15. Dimensions of solar Panel Used in residential and commercial areas [21].

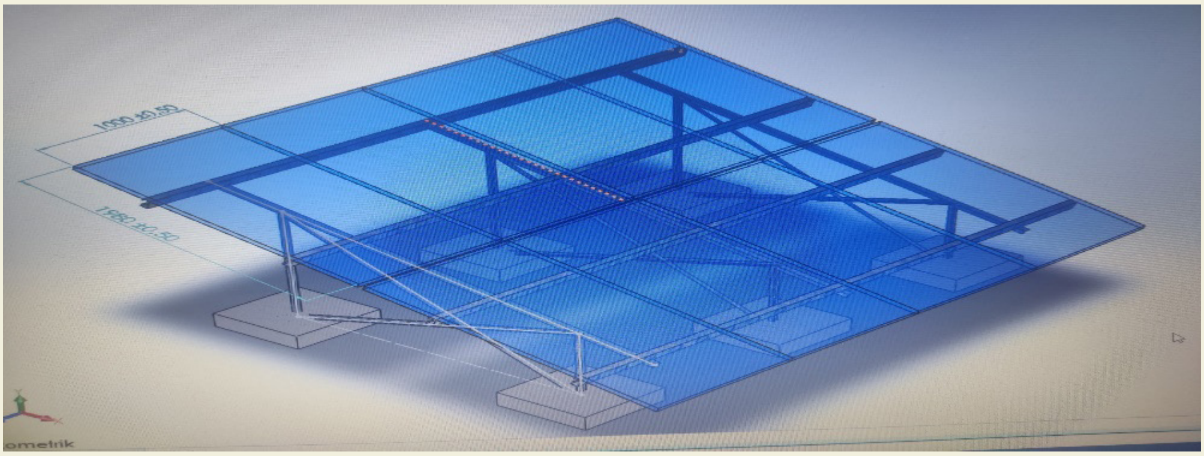

Figure 16. Dimensions of preferred solar panels in a selected model

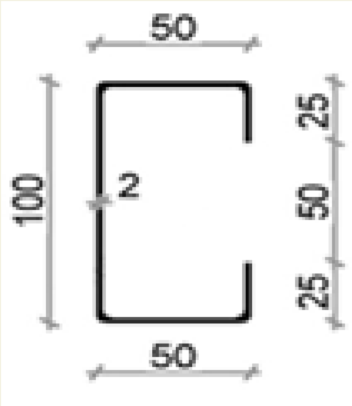

Figure 17. Dimensions of Dip Galvanised Steel with C Profile Structure [22]

optimization in the C-profiles, one of the model components, increase, stress at the static node points, i.e., the junction points of the elements, increases because the load is more pronounced at these node points. As the diameters of the circles to be removed from the areas subjected to optimization in the C-profiles, one of the model components, increase, static strain is generated and generally increases due to the logic of pixels exposed to load from the remaining areas, causing points to push against each other. As the diameters of the circles to be removed from the areas subjected to optimization in the C-profiles, one of the model components, increase, static displacements also generally increase due to the logic of pixels exposed to load from the remaining areas, causing points to push against each other, resulting in horizon-

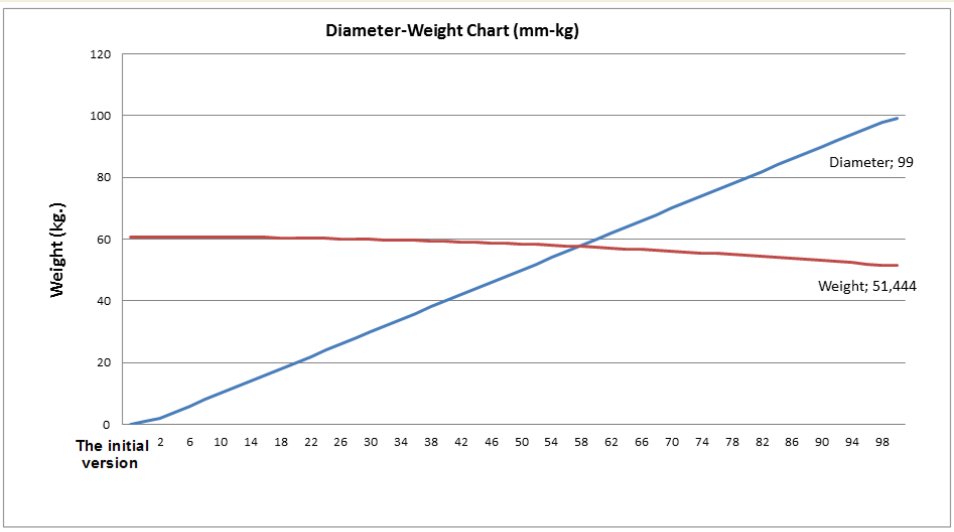

Figure 18. Reduced Weights of the Models

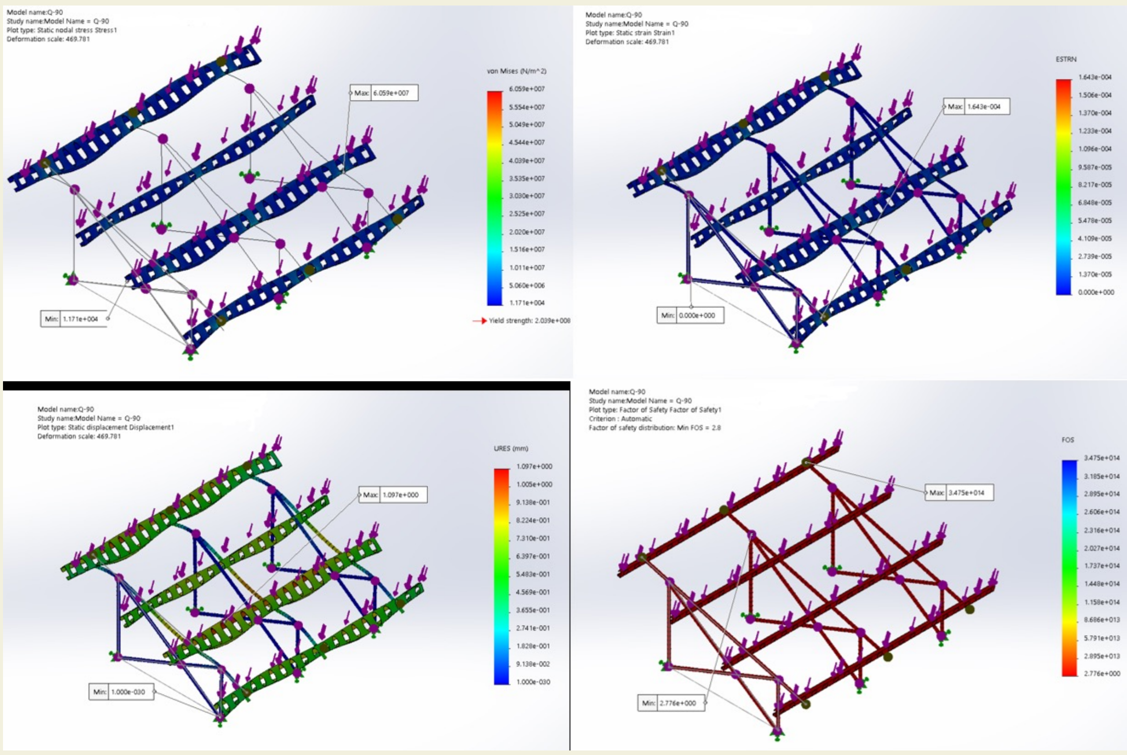

Figure 19. Proposed model "Model-Q-90" result graphs

tal displacements in the direction of the applied force on the component axis. As the diameters of the circles to be removed from the areas subjected to optimization in the C-profiles, one of the model components, increase, the safety factor generally decreases as the remaining areas are exposed to load. When the applied force on the models is reduced, the safety factor also increases. As the diameters of the circles to be removed from the areas subjected to optimization in the C-profiles, one of the model components, increase, deformations generally decrease as the area exposed to load decreases.

4. Conclusion

In this study, the structural and topological optimization methods were used to reduce the weights of C-profiles in steel construction solar panels. Initial model, models with lower constraints, and models with upper constraints considered as references based on experience, and other models treated as design variables. We conducted finite element analysis under an objective function to reduce their weights. The results, including Static Node Stress, Static Tension, Static Displacement, and Safety Factors, for the 52 models analyzed using finite element analysis were graphically presented, and we showed the maximum values in tables. This study has shown that optimization of models based on an objective function can contribute significantly to reducing their weights and costs, and design-based methods can be utilized during the installation of solar power plants. It emphasizes the applicability of design-based methods in the installation phase of solar power plants, affirming the potential for enhanced efficiency and cost-effectiveness in solar energy infrastructure.

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