# OPTIMUM DESIGN OF UNMANNED AERIAL VEHICLES USING STRUCTURAL OPTIMIZATION TECHNIQUES

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# ÖZET

Yüksek Lisans Tezi

İNSANSIZ HAVA TAŞITLARININ YAPISAL OPTİMİZASYON YÖNTEMLERİ İLE OPTİMUM TASARIM

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Teknolojinin gelişmesi ve dünya nüfusunun hızla artması ile araçların kullanım oranı büyük ölçüde artmıştır. Sıkı karbon emisyon yasaları ile endüstriler, araçların ağırlığını azaltmak ve dolayısıyla yakıt tüketimini azaltmak için optimizasyon teknikleri kullanarak birbirleriyle rekabet eder. Bu aynı zamanda maliyetin düşmesine neden olur. İnsansız hava araçları çok popüler hale geliyor ve savunma, gözetleme, haritalama, trafik kontrolü, doğal afet arama ve kurtarma vb. alanlarda kullanılıyor. Birçok insansız hava aracı türü var ve çalışmamız için Tricopter'i seçtik. Bu çalışmada, bir Tricopter model parçası üzerinde yapısal optimizasyon yapılmıştır. Öncelikle model CATIA üzerinde oluşturulmuş ve Hypermesh üzerinde analiz edilmiş, daha sonra model topoloji optimizasyon teknikleri kullanılarak optimize edilmiştir. Elde edilen optimum tasarım, ilk tasarıma göre %14.96 hafifletilmiştir.

**Anahtar Kelimeler:** İnsansız hava araçları, Tricopter, Optimizasyon, CATIA, Hypermesh.

**2021, x + 47 sayfa**

# ABSTRACT

MSc Thesis

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With the advancement of technology and the rapid increase in the world population, vehicles' usage rates have significantly increased. With strict carbon emission laws, industries compete against each other by employing optimization techniques to reduce the weight of cars, thereby reducing fuel consumption and reducing cost. Unmanned aerial vehicles are becoming very popular, and they are used in defense, surveillance, mapping, traffic control, natural disaster search and rescue, etc. There are many types of unmanned aerial vehicles, and for our study, we selected the Tricopter. In this study, structural optimization was made on a Tricopter model part. Firstly, the model was created on CATIA and analyzed on Hypermesh. Then the model was optimized using topology optimization techniques. As a result, the optimum design achieved is 14.96% lighter compared to the original design.

**Keywords:** Unmanned aerial vehicles, Tricopter, Optimization, CATIA, Hypermesh.

**2021, x + 47 pages.**

## ACKNOWLEDGMENT

I would like to express my sincere gratitude to my supervisor Prof. Dr Ali Rıza YILDIZ for the guidance and support throughout the thesis process. His patience, motivation, and immense knowledge helped me in the writing of my thesis.

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**Mohamed Sheriff JALLOH**

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## SYMBOLS and ABBREVIATIONS

| Symbols | Definition |
|---|---|
| C | Discharge current |
| V | Volt |
| KV | Kilo Volt |
| RPM | Revolutions per Minute |
| A | Ampere |
| Hz | Hertz |
| KHz | Kilo Hertz |

| Abbreviation | Definition |
|---|---|
| UAV | Unmanned Aerial Vehicle |
| DC | Direct Current |
| SAE | Society of Automotive Engineers |
| CAD | Computer-Aided Design |
| PRBM | Pseudo Rigid Body Model |
| ESC | Electronic Speed Control |
| CW | Clockwise |
| CCW | Counter Clockwise |

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# 1. INTRODUCTION

Unmanned aerial vehicles, also known as a Drone is an aircraft without a human pilot. It can be controlled remotely by a human or by onboard computers autonomously. It was first used in military applications, which was dangerous for humans. With technological advancement, unmanned aerial vehicles have become so popular today. Its usage has expanded in many applications such as surveillance, reconnaissance, aerial photography, agriculture, product deliveries, etc.

Recent advances in microchip technology, massive reductions in size and processing capabilities, and production and assembly costs have led to a new generation of vehicles. Technology that was previously only available for highly funded research departments and developed primarily for military purposes is commonly found in devices such as toys and mobile phones (Salem ve Gjertsen 2013).

Due to the increase in emission restrictions and the importance of fuel consumption, vehicles' weight reductions have become very important. Less weight equals less material and reduced cost.

The topology of a Tricopter model was carried out and successfully the optimum design was achieved. The optimum design achieved is 14.96% lighter than the original design.

## 2. LITERATURE REVIEW

In the thesis of Yücesan (2018), he conducted a shape optimization study for the holes of the metallic body beam laterally positioned in the upper body of the TAI T625 Original helicopter. In the research, MATLAB's multivariate optimization method was used together with the multiple starting point approach. As a result of the optimization, the part's weight was reduced without sacrificing strength and stability. There was an 8.69% weight reduction in the identical holes equidistant model and 10.5% with different spacing with the non-identical holes. In the same perforated pattern, it was observed that the holes took the shape of an ellipse, and in the non-same perforated design, the holes were circular as they moved from the centre to the tip. This is because the stress density decreases in the holes at the ends.

Bölükbaş (2012) developed a new model in order to find a solution to the breakages encountered in the tow hook used in buses. The casting was used to produce the part, and then topology optimization was carried out within limits suitable for this production method. The results show that there was a 32.45% and 45.49% reduction in maximum stress and weight, respectively.

Krishna and Anderson (2000) worked on improving the design of the upper swing arm used in the front suspension system of a car. After completing the analysis of FE (finite element) of the existing part, they determined different design ideas and calculated the improvement rates. Static analysis was implemented for the existing structure created with five other loading conditions in the ADAMS program. In the analysis, the weak areas in the structure were determined, and the areas that could be discharged and were insignificant in terms of stress were determined. With the considered design idea, the weight of the upper swing arm was successfully reduced by 15% and the maximum stress was reduced to 29%.

(De Oliveira Andrade et al. 2018) worked on the weight reduction of an Aircraft. In his work, topology optimization and size optimization were implemented. An optimization with an objective to minimize the compliance was done on the structure, and a Truss like structure was chosen. The chosen truss was exported to the CAD through the OSSmoth. It was sketched, exported to a STEP file, and imported again to the Hypermesh. On the other hand, a similar component without the tools of optimization was designed. Both results obtained were compared, and a 49% reduction of weight was observed in the optimized model.

Pan et al. (2007) analyzed the design improvement of the motor bracket part in a vehicle by using the finite element analysis. After getting bad results from the current designs, tests, and analyses they worked on before, they created topological and geometrical improvements on them. During the topology optimization, the optimum design conditions of the part were determined, then shape changes were made with a geometric approach. As a result of optimization, the weight of the model obtained was decreased by 12% compared to the first model, its structural strength increased by 50%.

Çelik (2017) applied topology optimization to increase the carrying level and reduce the weight of the honeycomb beams used in the structural systems of the buildings. As a result of the optimization, an optimal gap was obtained, and the resulting model showed better properties in terms of load-carrying capacity and internal stresses under load than honeycomb beams, which are still widely used. It has been stated that the load/weight ratio is high compared to other beams used in buildings. That is, although it has a low weight, it can carry higher weights.

Işık (2009) applied topology optimization to the fork flange part used in various places in heavy commercial vehicles. The new optimized design was found to be 12% lighter than the original design. In addition, it was determined that creating a conceptual model in the initial stages of the optimization process helps the optimum design to be achieved in a shorter time and with results that are closer to the desired target.

In the thesis of Doğan (2015), the motion equations of the crank connecting rod mechanism with a flexible connection element, which was created by the PRBM method, were solved in MATLAB. The data obtained from this solution were compared with the values obtained from the simulation of the mechanism in the ADAMS program. The optimized model showed a 63.167% reduction in volume compared to the first model. If the optimized model is used, there will be a 65.416% reduction in drive torque compared to the first model. This reduction means that the motor, which is the power source of the mechanism, consumes less energy.

In the study of Albak (2018), topology optimization was applied to a brake pedal, which is used in Formula SAE vehicles. He chose the material distribution method in the optimization process. Taking into account the production restrictions involved, the new design was made in accordance with the rules determined by the competition committee. The new design was calculated to be 11% lighter than the first design. However, since weight reduction was the main objective in this study, the increase in cost was neglected. Although the stress values increased by 5%, they still remained below the constraint value.

# 3. MATERIALS and METHODS

## 3.1. Unmanned aerial vehicles

In relation to wings of unmanned aerial vehicles, there are two classifications. These are:

- Fixed wings
- Rotating wings

Airplanes are examples of fixed-wing unmanned aerial vehicles wherein long runways are needed for flight takeoff and landing.
Rotating wings are the opposite. They don’t need runways for takeoff and landing.
Rotating wings are classified by the number of rotors available.
For example, a rotating wing unmanned aerial vehicle with three rotors is called a Tricopter. A four-rotor is called a Quadcopter, a six-rotor is called a Hexacopter, and an eight rotor is called an Octocopter.
Tricopters are preferable because of their greater maneuverability. They also have a better battery life system than others do (Şahin ve Oktay 2019).

Rotary wing unmanned aerial vehicles mainly comprise of

- propellers
- brushed or brushless motors
- ESC
- Battery
- Radio controller

Propeller selection:

The propeller is made of plastic structure that provides the following:

- Rigidity
- Lightness
- good lifting service
- higher aerodynamic efficiency (Das et al. 2019).

Propeller diameter and pitch are important in propeller selection. The distance between the motors should be bigger than the diameter of the propeller. The distance travelled by the propeller when rotating is called the Propeller pitch. Clockwise (CW) and counterclockwise (CCW) propellers are the last values to consider in propeller selection. While the Tricopter shows its official configuration, some propellers rotate clockwise, and the other propellers rotate counterclockwise (Şahin ve Oktay 2019).

Motor selection:

Unmanned aerial vehicles are driven either by the use of electric motors or by using an internal combustion engine. Internal combustion engines weigh a lot; therefore, their applications are limited (M Bharadwaj 2015).

Direct current (DC) electric motors can be divided into:

- brushed motors
- brushless motors.

Electric motors mainly comprise of two important parts – a stator, which is stationary, and a rotor that rotates. The stator can be called an armature, while the rotor can be referred to as a field or the opposite, which is based on how the magnets and windings are located and aligned on the stator and the rotor.

Brushed motors: Besides having low RPM and torque, brushed motors are simpler to use. For this reason, they can be used in small-sized unmanned aerial vehicles.
Brushed motors utilize carbon brushes to journey in every half cycle. This helps the motor shaft to turn in the same direction. This works perfectly, but after some time, the brushes wear out. Therefore, it needs regular maintenance.

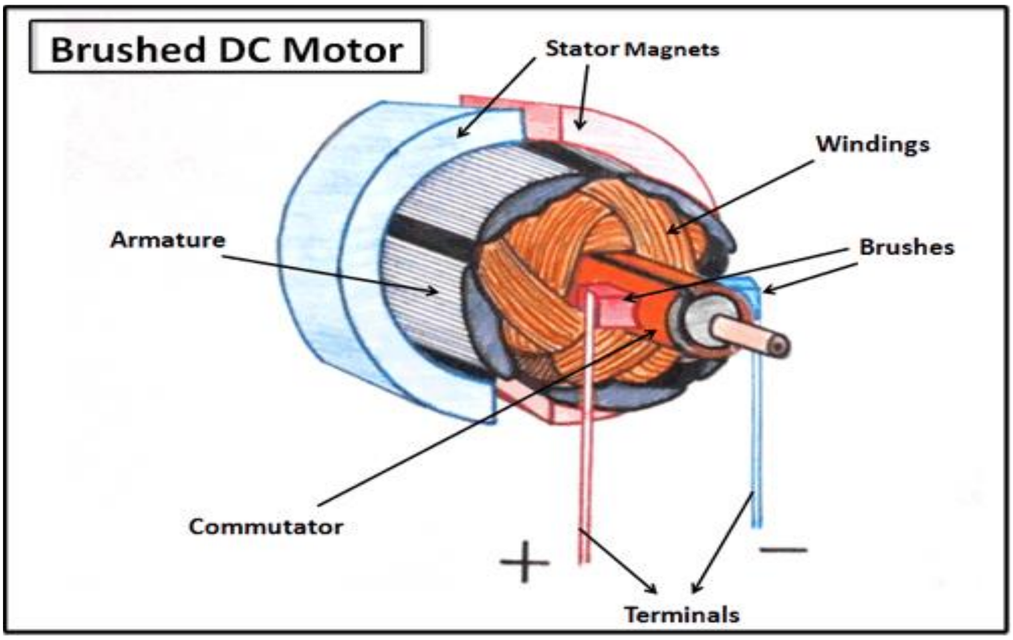


**Figure 3.1.** Brushed DC motors

Brushless motors: In brushless motors, the magnets are carried by the rotors while the stators contain the windings. Depending on the position of the rotor, it can be classified as Inrunners and Outrunners. In the Inrunners, the rotor is positioned inside, while as in the Outrunners, the rotor is located outside. Recently the employment of brushless motors is popular among aerial robotics due to their many advantages over brushless motors. The operations of these motors prove that they have high torque to weight ratios and also very high torque to watt ratios. This makes them a better choice compared to conventional motors. The electronic commutation in these motors is simple. Therefore, they are less exposed to mechanical wear and tear. Moreover, the cost of maintenance is low, and it uses simple electronics.

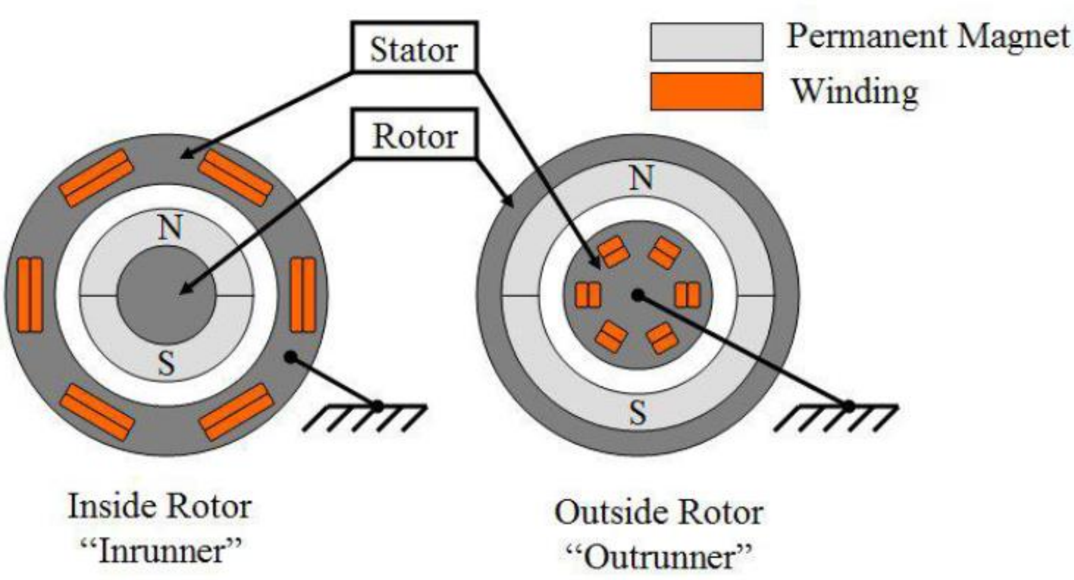


**Figure 3.2.** Brushless DC motor

The selection of the value of the motor in KV should be made carefully. When 1V is applied to the motor, the unit of the cyclic speed obtained is called the Motor KV value. If a motor of 650 KV is applied with a voltage of 10 V, the motor will rotate at 6500 RPM. 6500 RPM means that the shaft in the motor rotates 6500 times in sixty seconds (a minute) (Şahin ve Oktay 2019).

ESC selection:

An electronic speed control (ESC) has a low voltage source and is used on brushless motors that are powered electrically. It generates a three-phase current electronically. ESCs have the following purposes:

- controlling the electric brushless motors speed
- controlling the direction of the brushless motor
- sometimes can be used as a dynamic brake (Arega 2016).

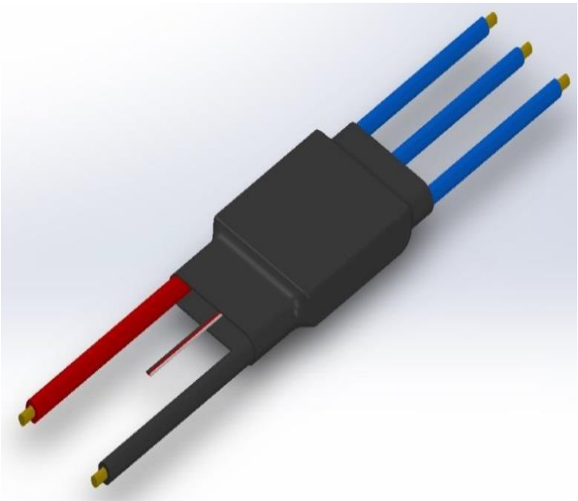

**Figure 3.3.** ESC connection cables

From the figure above, we can deduce that there are three types of cables in the ESC. The first type of cables (red and black) is the battery power cables. These two cables are the power cables and are fixed to the battery. The ESC and the battery used should have the same compatibility properties. The second type of cables is Servo cables. They consist of three thin cables that are connected to the control board. Their function is to receive information about the speed at which the motor should rotate. The last type of cables (blue colored) are connected to the motor (Şahin ve Oktay 2019).

The desired rotation can be done by replacing any two of these cables. If the desired rotation is not attained, you must replace the orientation of the motor connection cables, as can be seen below.

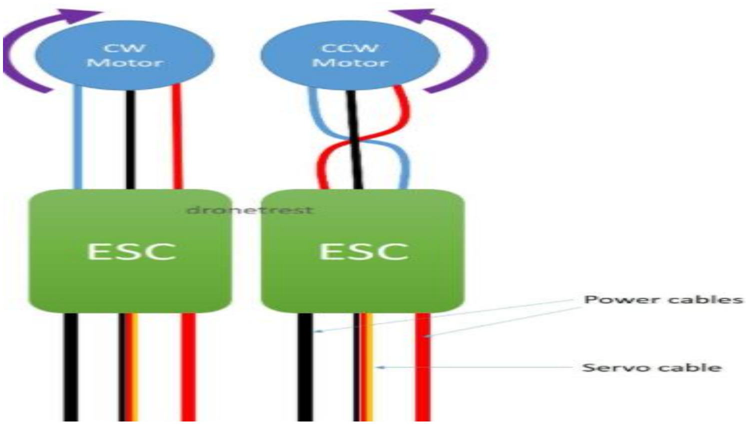

**Figure 3.4.** The orientation of ESC cables

Battery selection:

The source of the power of a Tricopter is mainly the battery. A lithium polymer battery of 3000 mah can be utilized to sustain high current loads and to reduce the resistance for heavy-duty discharge (Das et al. 2019).
In the development of a UAV, the battery and its capacity are very important. Factors such as agility, the endurance of the flight, hovering capability, etc. are defined by the capacity of the battery (M Bharadwaj 2015)

The selection of a Lipo battery depends on three parameters. These are:

- Cells
- Electric capacity
- Discharge current

Cells: In batteries, the number of cells is indicated by S, P, or both. There's a rating in each cell in a Lipo battery which is 3.7V. For example, a battery with a rating of 3S means that the battery can produce a voltage of 3*3.7V = 11.1V. A battery of 2S2P means that two cells are in series, and two cells are in parallel, which equals four cells (Şahin ve Oktay 2019).

Electric capacity: The electric capacity of batteries is expressed as Ah or mah. Ah as in (ampere per hour) and mah as in (milliampere per hour). A battery of higher capacity is required because it has a longer run time than a lower capacity battery. For example, a tricopter that utilizes 9A on a 3000mAh battery is able to give 20 minutes of flight.

Discharge current: The discharge current indicates the intensity of the maximum current and is denoted by C. A rating of 1C clearly states that it takes one hour for the whole battery to get discharged. A battery that is rated 1000mah and 20C means that the battery delivers 1*20 = 20A of current. A similar battery but with a 1C rating discharges 1A in an hour. The battery with a 20C rating discharges 20A, which is fast, and this indicates a reduction of flight time (M Bharadwaj 2015).

For example, a battery with an electric capacity of 3Ah and with a discharge rate of 50C can discharge a maximum of 50*3 = 150A.

The flight time can also be determined as:

Flight time = (60 minutes) / (C rating)

= (60)/40

= 1.5 minutes.


**Figure 3.5.** Turnigy battery used in UAV

Lithium polymer batteries are the ultimate choice for UAVs that utilizes current as their main power source. Lithium polymer batteries are very well known when it comes to UAV because they can produce high current due to their high power, longer life span, and less weight.

Below are the advantages and disadvantages of Lipo battery cells when compared with other batteries, such as ni-mh and ni-cd.

**Table 1.1** Advantages and Disadvantages of Lipo batteries

| Advantages | Disadvantages |
|---|---|
| They are lighter in size. | They have a small life span. |
| Their capacities are very high. | The chemical shape is sensitive and is liable to burn. |
| In Lipo batteries, high discharge currents can be allowed. | |

Radio controller (RC):

A radio controller is used to send signals and commands to control the flight. The most widely used frequency band is the 2.4 GHz frequency band. The transmitter and receiver commonly use this frequency band to communicate with the flight controller. The function of the radio controller is to convey signals cordlessly to the receiver. The receiver, which is onboard, is fixed to the flight controller. From the figure below, it can be seen that there are two sticks. The right stick is responsible for controlling the roll and pitch angles while the left stick controls the throttle and yaw (Salem ve Gjertsen 2013).

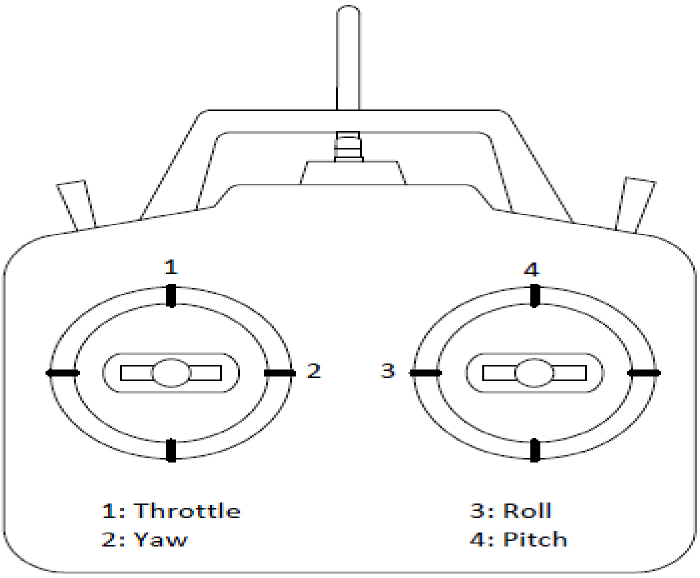


**Figure 3.6.** Radio controller

### 3.2 Tricopter

Besides the complicated structure, Tricopters have several advantages as compared to other unmanned aerial vehicles. These advantages can be such as flight time and maneuverability. The Y and T forms of Tricopters are greatly preferred among different designs. These can also be named Ycopter and Tcopter based on their structures. From the name Tricopter, it can be understood that it has three propellers.

**Figure 3.7.** A Tricopter

Tricopters comprise three propellers, one servo motor, three brushless motors, three ESCs, and a control card. For easy maneuverability, servomotors are used. Servomotors also provide better energy efficiency by using less energy as compared to a quadcopter using one motor.

Mathematical model:

Tricopters consists of rotors that are usually T-shaped or Y-shaped. They are usually 120 degrees apart from each other.

There are forces acting on a Tricopter when it is flying. These forces include Drag, Thrust, Lift and Weight.

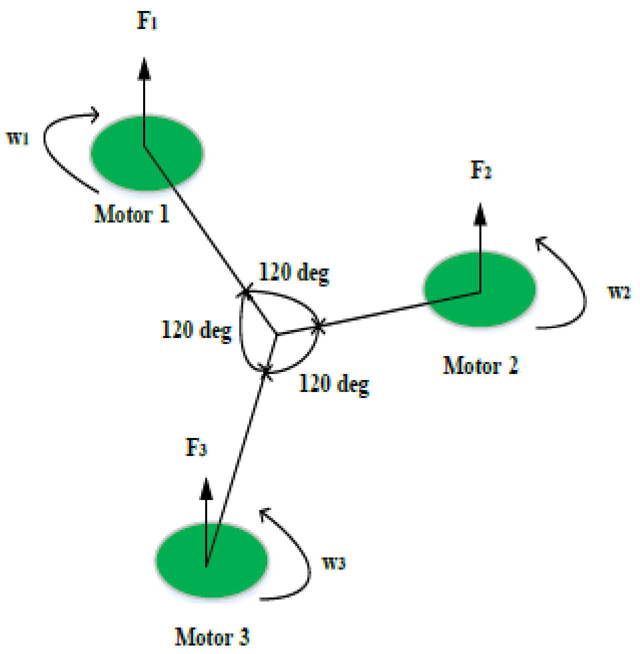


**Figure 3.8.** Forces on a Tricopter

Balancing the forces on the Tricopter:

Summation of forces on the y axis = 0

$\Sigma Fx = 0$

Force = mass(m) * acceleration(a)

For constant velocity, acceleration equals zero

Therefore, the force equals zero

Summation of forces on the x axis:

Thrust force - Drag force equals zero

As a result, $T - D = 0$

That is, thrust equals Drag

Again, considering the horizontal axis

Lift force - Weight force = 0

$L - W = 0$

Therefore, the Lift force equals the Weight

The stability of the flight can only be maintained at a high altitude if the thrust force (T) is the same as the drag force (D). Similarly, the weight of the Tricopter (W) should be equal to the lift force (L). For the vehicle to accelerate, the drag force(D) should be lesser than the thrust force(T)

Moment of inertia of a tricopter:

The inertia of a tricopter can be calculated by considering the following assumptions:

- the fuselage is rectangular in shape
- the motors are cylindrical in shape
- a neglection of the inertias of the round rods of the axes (Naik et al. 2014)

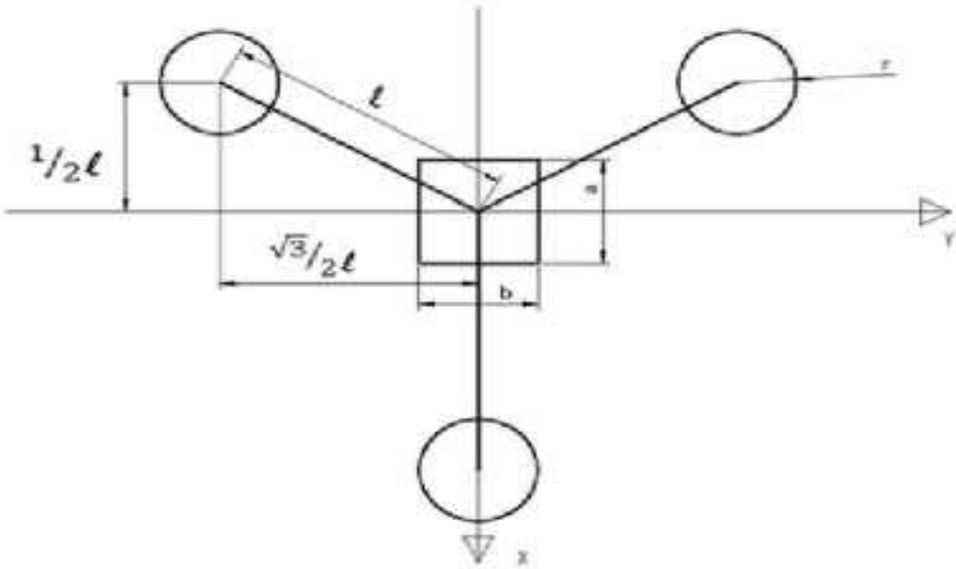


**Figure 3.9.** Free body diagram of a Tricopter

Moment of inertia of each axis;

Considering the overall monent of inertia in the x direction

$Ixx = \frac{3}{2}ml^2 + \frac{1}{12}mob^2 + m(3r^2 + h^2)$

The overall inertia about the y direction:

$Iyy = \frac{3}{2}ml^2 + \frac{1}{12}moa^2$

From the z direction, calculating all the moment of inertia:

$Izz = \frac{1}{12}mo(a^2 + b^2) + 3ml^2$

### 3.3. Methods

In this study, the tricopter below was analyzed using the finite element method. A static analysis was performed first on the part. Following the analysis, the part was structurally improved by using optimization methods.

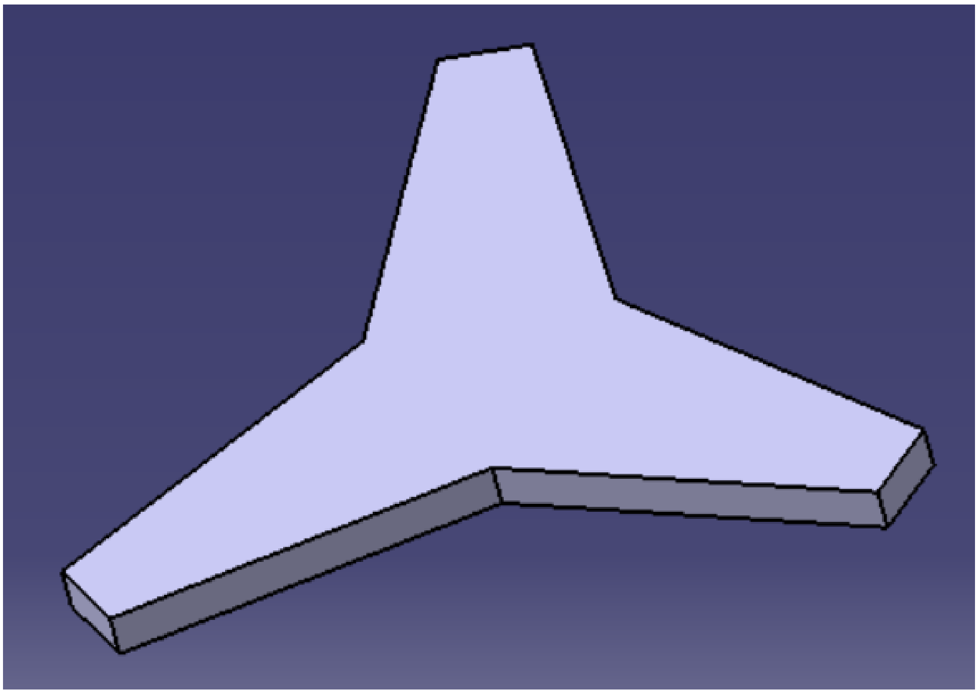

**Figure 3.10.** Tricopter model

The linear static analysis was first applied to the part. Later topology optimizations were carried out. Information about the methods used in detail can be found in other sections.

#### 3.3.1 Finite Element Analysis

The laws of physics and mathematics help us understand all phenomena in nature. Each event has a magnitude, which is represented by mathematical equations. These mathematical equations can be either algebraic, differential, or integral. Complex problems can be simplified by dividing them into sub-problems. To solve a complex problem, sub-problems are combined and then solved. For example, the problem to be solved can be arranged freely with small finite elements. Complex geometries can be easily created this way. The results found are usually an approximate solution to the problem and are sometimes used directly, sometimes corrected with a coefficient. Due to the complexity of problems in engineering practice, an acceptable solution is often preferred over the exact solution of the problems. (Bostancı 2002).

The basic ideas behind the solution methods known as the finite element method today date back centuries ago. For example, centuries ago, scientists drew a polygon around a circle to find the circumference of the circle. The higher the number of polygons, the closer they were to the correct results. The finite element method known today was introduced by Turner, Clough, Martin, and Topp in 1956. In that study, the finite element method was used for stress analysis of the fuselage of an aeroplane. Nowadays, with the development of technology, problems that can take a long time to solve can be solved in a short time. All this is possible thanks to computer technologies, and it gives very realistic results (Turner et al. 1956).

The advantages and limitations of the finite element method are as follows:

- Its geometry enables complex shapes to be easily examined. Different finite elements can be used in the analysis and can be analyzed by dividing them into sub-regions.
- It can be easily applied to systems with different and complex material properties. The irregularity and non-homogeneity of the geometry is not a problem for this method.
- Continuous, discontinuous, or variable loads can be easily examined.
- Besides having a physical meaning, it also has mathematical foundations.

Besides these advantages, the finite element method also has some limitations:

- Working with small element sizes should be done to make the results more realistic. If the element sizes used are very small, the computer features used should be very good.
- There is too much input data, and they must be entered correctly. Program data should be kept under control.

As with all other systems and analysis methods, the results of the finite element method should be carefully examined, and the most accurate results should be obtained by comparing them with the real data.

The Element Types Used in the Finite Element Method:

Some element types used in this method are described below:

Three-dimensional bar element: It is a general-purpose finite element type and is capable of performing three-dimensional operations. This element is also called the spacebar element. It is possible to express the element with two nodes in space. There are 12 degrees of freedom for the two nodes at either end. There are three offsets and three freedoms of rotation for each node. In order to define the element, node coordinates, modulus of elasticity of the material, shear modulus, cross-sectional area, section moment of inertia, torsion constant, the deformation factors perpendicular to the bar axis are needed.

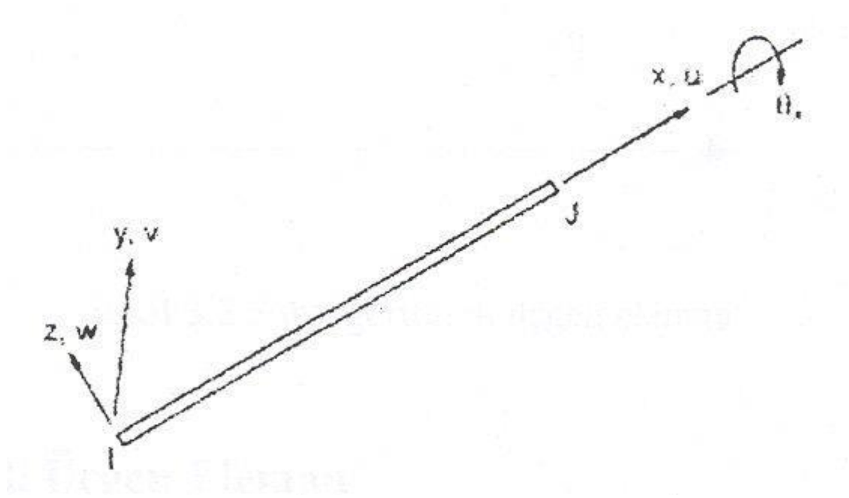


**Figure 3.11.** Three-dimensional bar element (Bostancı 2002)

Constant strain triangular element (CST):

It is a constant thickness element that connects three nodes and can be defined by a total number of six degrees of freedom. The displacement field is linear inside the element and along the edges. Stress values are constant within the element boundaries. The element displacement area is shown below.

$$u = a1 + a2x + a3y \quad (4.1)$$

$$v = a4 + a5 + a7y \quad (4.2)$$

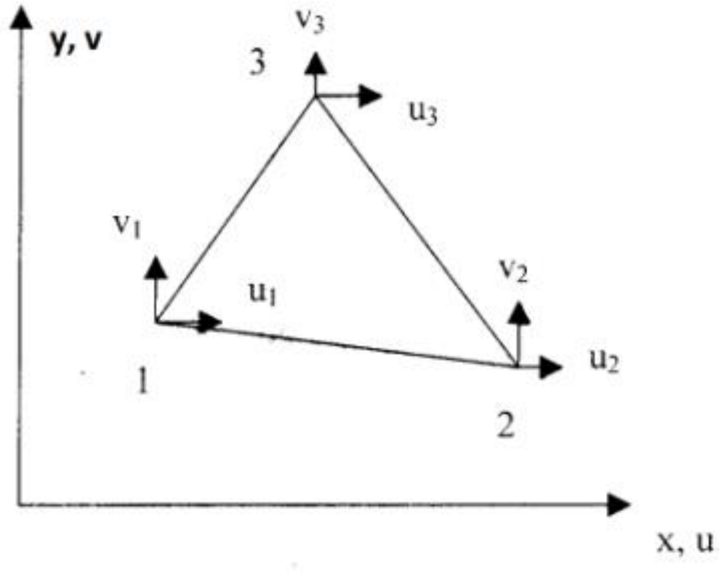


**Figure 3.12.** Three-dimensional triangle element (Bostancı 2002)

In finite element models, the constant stress triangular element will give good results in regions with small stress gradient properties. In other cases, the use of constant stress triangular elements may not give good results.

Linear strain triangular element (LST):

Unlike constant strain triangular elements, there are joints on the edges as well as on the corner points. Each element has six nodes and 12 degrees of freedom. Models made with linear stress triangular elements for places subject to bending only will have very good approximations for displacement and stress fields. Unlike the CST element, the stress size changes linearly with the x and y coordinates in the LST element.

$$u = a_1 + a_2x + a_3y + a_4x^2 + a_5xy + a_6y^2$$

$$v = a_7 + a_8x + a_9y + a_{10}x^2 + a_{11}xy + a_{12}y^2$$

Double linear quadrilateral element:

Another element type that can be used in two-dimensional problems is the double linear quadrilateral element. There are four nodes in the corners of the element. The element has 8 degrees of freedom with respect to the nodes. Displacements are given below.

$$u = a1 + a2x + a3y + a4xy \quad (4.3)$$

$$v = a5 + a6x + a7y + a8xy \quad (4.4)$$

The reason why this element is called double linear is that the displacement connections u and v are obtained by the product of two linear polynomials.

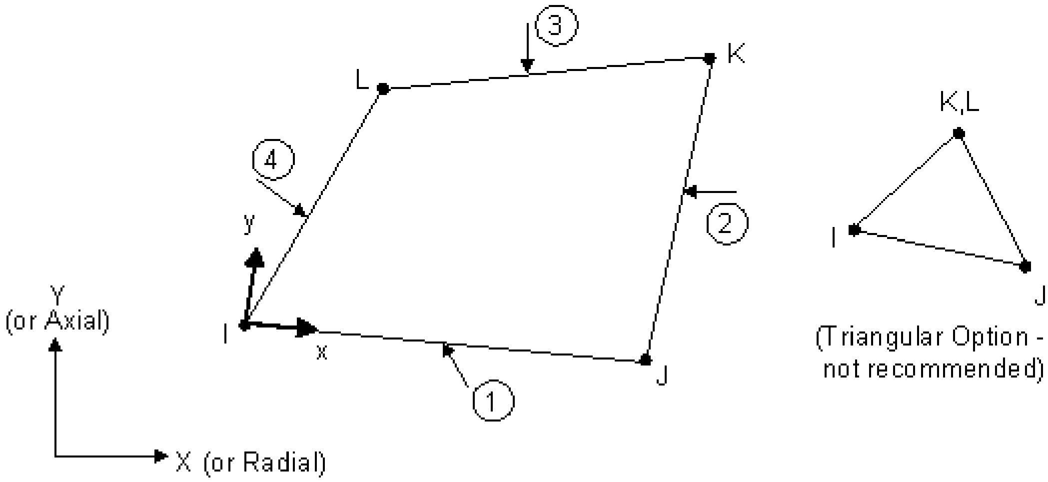


**Figure 3.13.** Double linear quadrilateral element

Shell elements:

A general shell element, along with the membrane, should be able to represent the bending effect. For example, a simple quadrilateral element with four nodes can be defined. The nodes that define the item may not all be on the same plane. This causes deterioration of the element. The deterioration of the element affects its performance negatively. The biggest advantage of this four-node element is that its formulation is simple. In general, it is recommended to use a larger number of simple elements rather than using fewer, more complex elements. The major disadvantage of the four-node shell element is that flat, curved surfaces are represented by plane elements or elements with a small amount of distorted shape. Curved surface elements based on shell theory eliminate the problems created by planar elements. However, it also brings different difficulties.

Much more geometric information is needed to describe the curvilinear element. The formulation of the shell element is much more difficult than the formulation of planar elements.

Four-node and four-sided elastic shell element:

This element is capable of bending and carrying membrane loads. The element can carry loads in the plane and loads perpendicular to the plane. Each node has six degrees of freedom, three of which are offset in the x, y, z-direction, and three are free to rotate around these axes. The element is defined by four nodes, and variable thickness is allowed. For elements with variable thickness, the thickness should vary within the elements evenly. This type of element is used to model smooth curved surfaces as well as plates. A large number of this element should be used to get a good approach on curved surfaces. Due to the simplicity of the formulation, it is more advantageous than other types of elements.

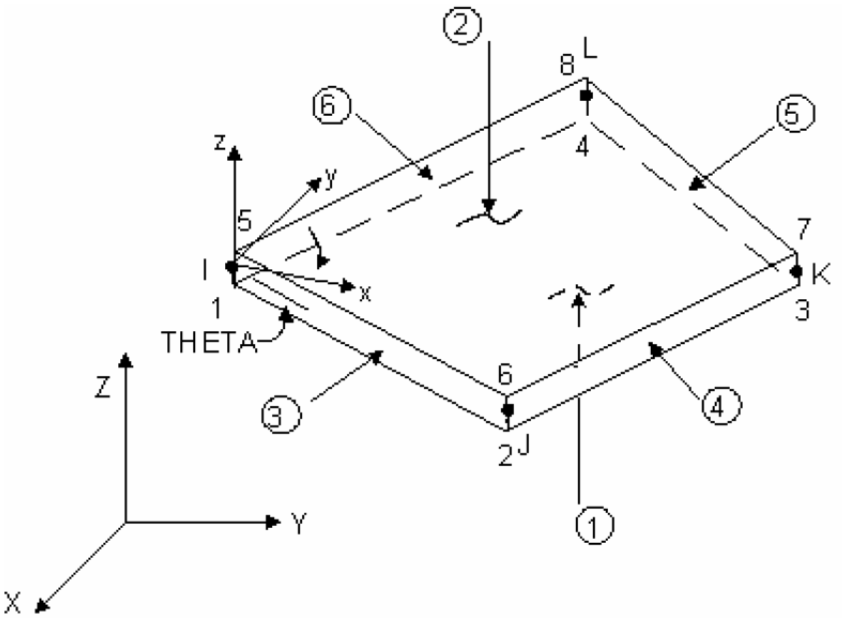


**Figure 3.14.** Four-node and four-sided shell element

The assumptions made while modelling in the finite element method are as follows.

- The CAD model to be used must be able to represent the real part sufficiently.

- Regions made with aesthetic concerns in design can be ignored in terms of strength.
- Losses that may occur due to friction in the system are neglected.
- The dissolution that may occur over time at connection points can be neglected.
- All resources in the system can be considered ideal and perfect.
- Damages that may occur in fasteners such as bolts and nuts can be neglected.

In order for the solutions of the part modelled in the finite element method to be as close as possible to the real values, the model should be modelled as close to reality. There are some points to be considered for this.

- While modelling the part, the network structure should be as smooth and orderly as possible. However, a denser network may be allowed in regions critical to loading conditions.
- Quadrilateral elements give more accurate results than triangular elements. Therefore, the rectangular-shaped elements should be used. If it is necessary to use triangle elements, triangle elements with large angles should be used.
- If the part being analyzed is symmetrical, it can be modelled for a certain part instead of the whole part.
- Attention should be paid to the dimensioning of the element types used in modelling. Small and smooth transitions should be provided.
- In the analysis of systems with a complex structure, the entire structure is analyzed with a relatively rough network structure. The results of this analysis are used as a boundary condition of the region that is desired to have detailed information within the structure. The analysis is made with a more dense network structure for this region.

### 3.3.2 Search Methods

Algebra-based methods:

These methods can be grouped into two as direct and indirect methods. In the indirect method, the gradient of the objective function is obtained by equating to zero, and generally, nonlinear equations are solved to reach endpoints. In the direct method, a search is made depending on the gradient at a point determined in the function. It is one of the methods developed for the optimization of continuous functions (Öztürk 2002).

Sequential methods:

It is a method that searches from infinite space elements in a certain search region or in a discrete state by trying different elements each time as an objective function. It seems like a simple method, but the size of the search space increases the search time enormously (Öztürk 2002).

Random search:

When systematic approach search algorithms fail, non-systematic methods, namely random search methods, should be adopted. The points in the search area are selected randomly, and their suitability is evaluated. The search continues until the appropriate value is found. This method does not use information obtained from discoveries (Öztürk 2002).

If random search and algebraically based methods are applied together, the success rate can be high for functions that do not have too many local maxima and minima. However, since the search trials will be performed in isolation from each other, the result showing the whole curve cannot be found. During the search, each point of the search zone is evaluated equally. The number of points evaluated in the region with low conformity value and in the region with high conformity value is equal.

Evolutionary Algorithms:

These methods make optimization by imitating the natural evolution process. They are computer-based problem-solving techniques based on computational models of the evolutionary process in design and implementation.

Evolutionary programming (EP):

The mutation operator to obtain P new individuals uses the P chromosome created with random values. With a probabilistic selection, P individuals are chose to create a newly formed generation from the population that reaches the 2P population. In order not to lose the optimum ratio achieved, the individual with the highest fitness value in the society should always be found.

Evolutionary strategies (ES):

It is a method with a linear data structure in which the reproduction is based on a controlled change and does not rely on matching, but the genes are only composed of numerical values. In reproduction, each gene value of all individuals is differentiated according to a normal probability distribution, which is altered by evolutionary methods and determined by the standard deviation specific to the individual's gene. In this method, P individuals with the highest fitness value of parents and new individuals are selected to create a new generation. Rearranging is an important parameter, which differs from the evolutionary algorithm.

Genetic algorithms (GA):

It is inspired by living organisms. Living things have evolved for years based on natural selection and the principle of survival of the fittest. (Beasley ve ark. 1993). The basis of the genetic algorithm follows the evolutionary process; it is always open to development as it is still the subject of research, which of the biological processes are essential, which are important or unimportant in evolution.
The genetic algorithm works on groups of individuals, the sequence representing the solution to the current problem. Each of these sequences is referred to as chromosomes.

All individuals are given a value of suitability according to the success level of the solution. Because of the selection process with a predetermined strategy, new generations are obtained by ensuring that a crossing process reproduces individuals with sufficient levels of fitness values. The content of each generation that is formed as a result of reproduction has more features that increase the fitness value found in their ancestors. Thus, as the number of generations increases in society, individuals with appropriate values become more common. If the genetic algorithm is well designed, the community being studied will converge to a suitable solution. The genetic algorithm provides the opportunity to successfully apply and develop in a wide space where there are problems that are difficult to solve with various methods (Beasley ve ark. 1993).

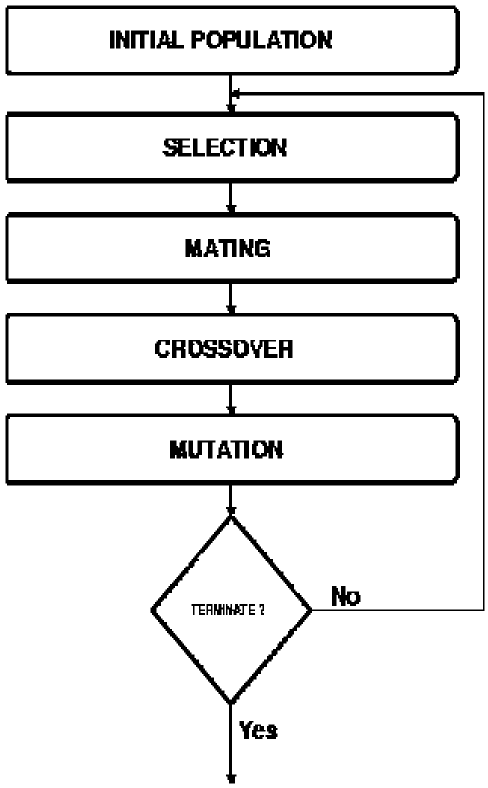


**Figure 3.15.** Genetic algorithm flowchart

By using genetic algorithm, we can also find the optimal values for a better ride comfort in vehicles. Determining the values include using the vehicle and the human body models (Yildiz 2019)

### 3.3.3 Optimization Methods

Definition:

In its simplest terms, optimization can be defined as the optimal use of the limited resources available. Mathematically, optimization can be defined as minimizing or maximizing a function. It is a technology that determines the best possible efficient utilization of available resources (labour, time, capital, processes, raw materials, capacity, equipment) in a program to reach specific goals (cost reduction, profit maximization, capacity utilization, and efficiency maximization).

Modelling and analysis are considered as the two main components of optimization. While modelling is a mathematical expression of real-life problems, the analysis aims to find the best solution that provides this model.

The main objective of optimization is to specify the amount of products that will achieve highest profit or the lowest cost taking into account the available constraints. The optimization technique is applied to many sectors in industries. Changing and developing technological systems, limited resources, increasing competition, and the inadequacy of the known classical methods (mathematical or non-mathematical, analytical or numerical) and solving these type of problems gives importance to the concept.

This program is utilized to accelerate the process of decision-making. By the usage of effective, accurate, and real-time solution to real-world problems it can also improve the quality of decision making. Besides economic gains, customers, employers, and employees; It is a method that is efficiently used in the decision making process in optimization and to also used to increase the quality of resources in the system.

Creation of optimization models:

Models are small-sized structures that reflect the properties of large systems frequently used in engineering and basic sciences. Models usually contain details that reflect the characteristics of the system and include the actual purposes of the model. For example, when examining the crash test and aerodynamic nature of a vehicle in the design phase, it is performed using vehicle models instead of real vehicles (Türkay 2018).

Optimization models are mathematical expressions that reflect the functioning and properties of the system and include its interaction with other systems within and around the system. The working logic of optimization is as shown below.

$$\begin{cases} \max z = f(x,y) \\ k.s.\, g(x,y) = 0 \\ h(x,y) \leq 0 \\ x \in \Re^n \\ x \in \{0,1,2,\dots,m) \end{cases} \tag{5.1}$$

The expression z = f (x, y) specified in Equation 5.1 refers to the objective function, x and y to the decision variables, and n to the space size.

In optimization problems, it is aimed to find x and y values that will maximize the function z = f (x, y). The system properties are determined by the constraints g (x, y) and h (x, y).

Classification of Optimization Problems:

Most of the optimization methods are limited to specific problem types. In order to get results, the optimization method appropriate to the characteristics of the problem should be chosen. The classification of optimization problems is based on the mathematical properties of the target function, its constraints, control variables, and search method.

Trial and error optimization:

Trial-and-error optimization is adjusting parameters that affect data without too much information. It is the method that enables experimental study and discovery. The opposite of this method is the functional approach, where the process is defined by the mathematical formula.

Single and multi-parameter optimization:

If there is only one parameter, optimization is a single parameter. If there is more than one parameter in optimization, this optimization is multi-parameter.

The difficulty of the optimization increases when there is an increment in the number of dimensions.

Static and dynamic optimization:

Static optimization is time-independent; dynamic optimization provides data depending on time. For example, for a person who has several ways to go from home to work, the best way can be examined. In terms of distance, the problem is static. If the aim is to reach the job as soon as possible, the physical condition of the road to be travelled, traffic, etc. The problem is a dynamic optimization problem because the factors change over time.

Continuous and discrete parameter optimization:

Continuous parameters take an infinite number of values, while discrete parameters take a limited number of values. For example, since the tasks are given as a list are independent of each other, they are in the optimization class with discrete parameters. The continuous optimization is finding the highest or lowest value of a function

Limited and unlimited Optimization:

Sometimes limits are placed on the values that parameters take. Limited optimization adds equations and inequalities that define constraints to the objective function. In the unlimited optimization method, parameters can take any value. Limit parameters can be converted to unlimited parameters by removing the boundaries of the parameters.

Random and minimum search algorithms:

Various algorithms try to bring the appropriate value closer to the minimum by adjusting the initial value of the parameter.

Although this method is fast, it can reach local minimums. Random methods use probability calculations for solving parameters. These methods are slow but give better optimum results.

### 3.3.4 Structural Optimization

This optimization technique is classified into three classes which are topology, shape, and size optimization. After topology optimization is applied to the part, shape optimization is applied, and the outer part and holes of the part are shaped accordingly. If necessary, the final shape is given to the part by applying size optimization later.

Structural design optimization procedures can also be used to optimize the driving force required to open and close the trunk lid of the vehicle (Yildiz 2021).

### 3.3.5. Shape optimization

In shape optimization, the aim is to make the outer borders and holes of the structure optimized by changing the shape. Local stress problems can also be determined by using this type of optimization

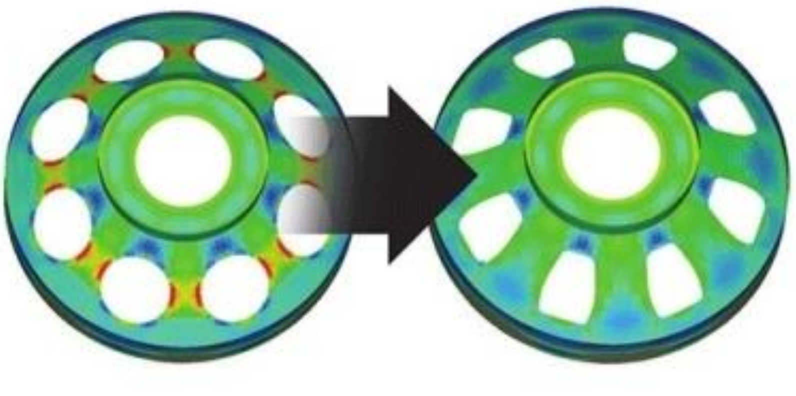

**Figure 3.16.** Representation of a shape optimization

### 3.3.6 Size Optimization

In Size optimization, the most suitable model properties (material properties, thickness, size) of the parts are found.

### 3.3.7 Topology Optimization

Design methods that makes it easy to create a part that weighs less, has a longer durability and which can also fit in a limited space should be designed. . It makes it easier to design a part that alrerady has a previous concept or design and if there is no previous work, conceptual designs can be created. Standard optimization may be applied directly to the design. Parameters are used to determine the dimensions and other design variables.
Getting the best material distribution based on the constraints is the objective of any topology optimization. The voltage, displacement, and also displacement are restrictions that are determined for most optimization processes. These restrictions play a great part in the optimization process. They are used by the optimization program to discharge on the part and thereby bringing the mass and volume displacements values to the desired level.

Topology optimization:

Topology optimiztaion is carried out on Truss systems which are discrete structures. They are very popular and are an issue emphasized in many industries. The most widely used method in such structures is the basic building approach. Optimization preserves the most important bars in the basic structures and tries to get the best topology by removing the unimportant ones.

Homogenization method:

The shape in this method is homogenized and the formation is considered as microstructural and composite. In this method, a microstructure can be classified into three classes as generalized porous material containing zero material (the size of the hole = 1), isotropic material (the size of the hole = 0), and orthotropic material (0 < the size of the hole <1) (Göv ve Kütük 2007).

The method uses the dimensions of the hole and the orientation angle variably to find the structure with minimum flexibility or maximum stiffness on the model subject to volume or mass constraints. The amount of available material is variably redistributed to the volume by utilizing its microstructure properties.

Density method:

The density method is also known as the material distribution method. In this approach, a design variable is utilized directly which is defined as the material density. If there's no problem with multiple design variable, then homogenization approach may be carried out primarily based totally at the goal function. This is be carried out when the space direction which is found in the element may be defined.

# 4. RESULTS and DISCUSSION

## 4.1 Creating the part from CATIA V5

The model was first created on CATIA V5 and then imported to Hypermesh.

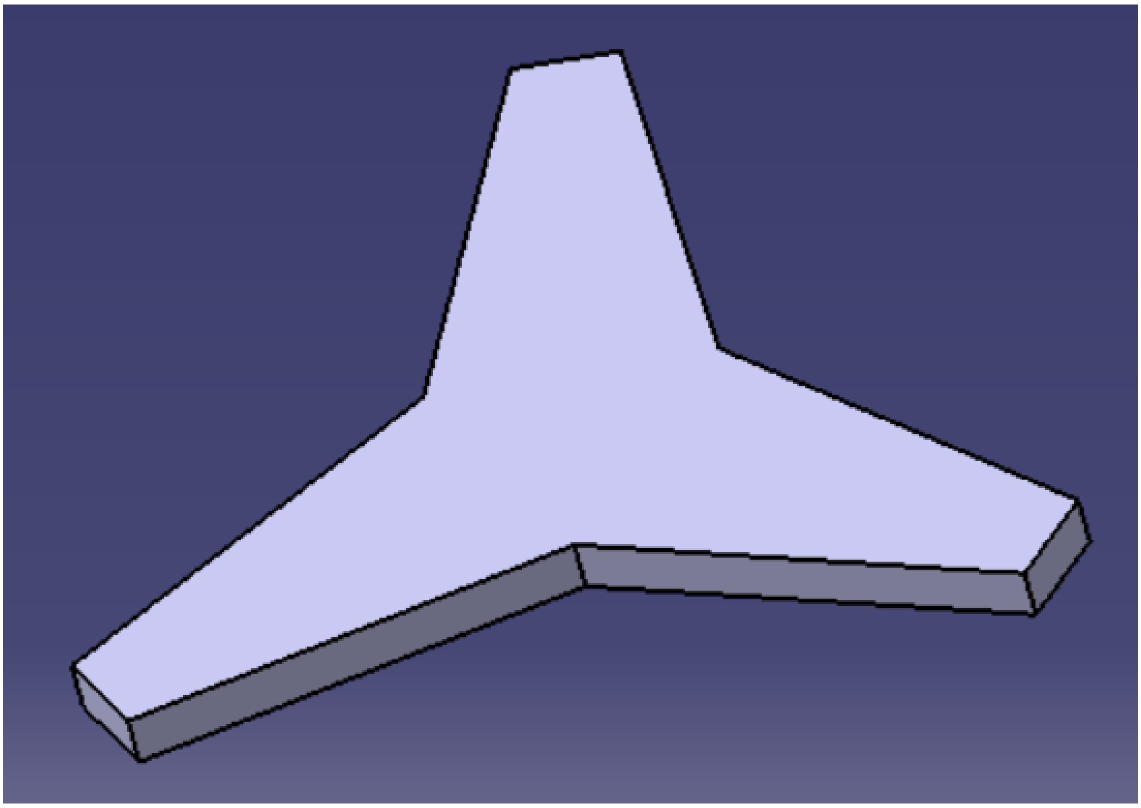

**Figure 4.1.** Finite element model

## 4.2 Linear Static Analysis

The finite element model was prepared according to the finite element theory in Hypermesh 2019.1 program.

In the Hypermesh program, the following parameters were created.

- Meshing: Volume tetra solids were used for the meshing. Mixed 2D and 3D elements were selected, and the element size used was 3.0.

- Material: Polyethylene was chosen for the material. The Youngs modulus, Poisson's ratio, and density of Polyethylene were determined as seen from the figure below. MAT1 was selected for the card image.

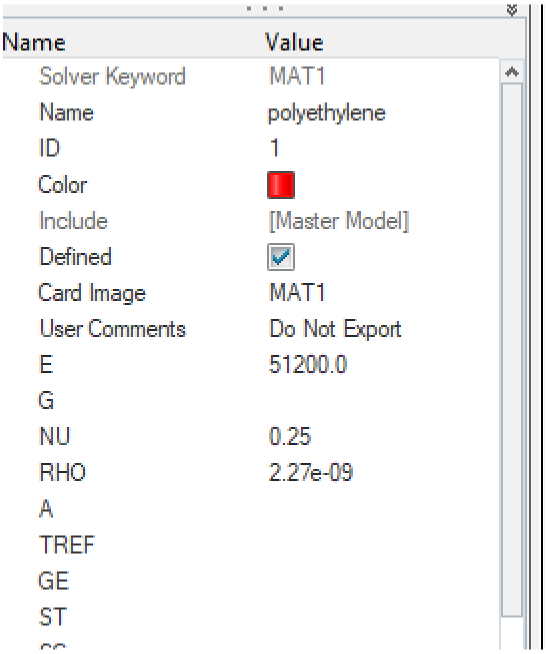


**Figure 4.2.** Material properties

- Property: By selecting PSolid for the card image, the property was created and assigned to the material
- Component: The component was created. Both the material and property were assigned to it.

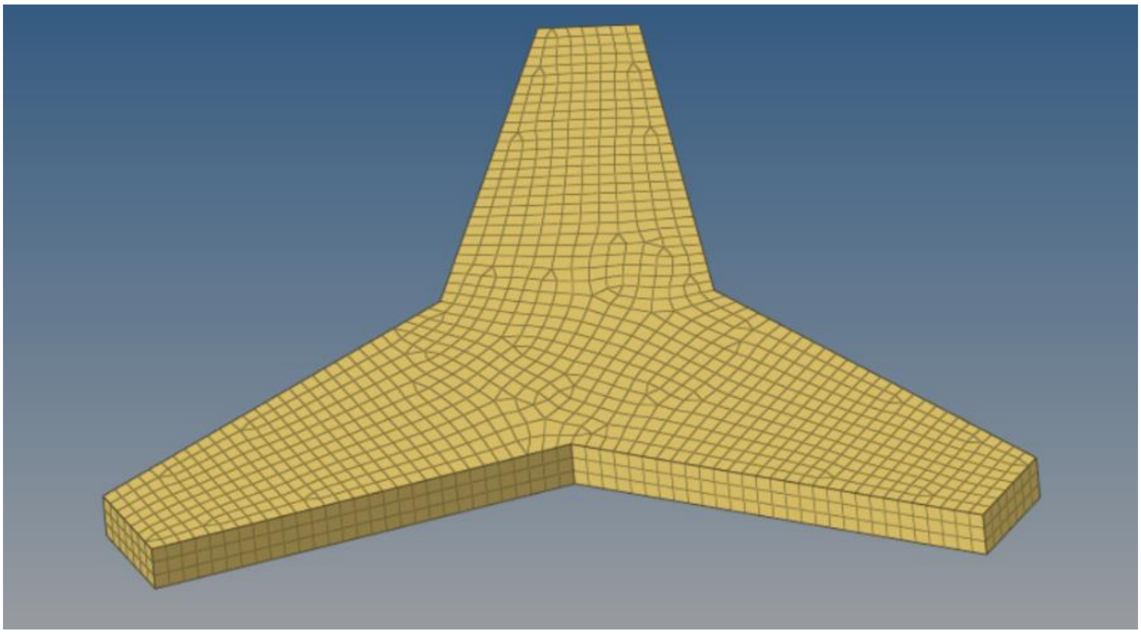

**Figure 4.3.** Meshed model

- Load collectors: The load collectors such as the SPC were created on the model.

Load steps were created, and the analysis was completed, as shown in the figure below.

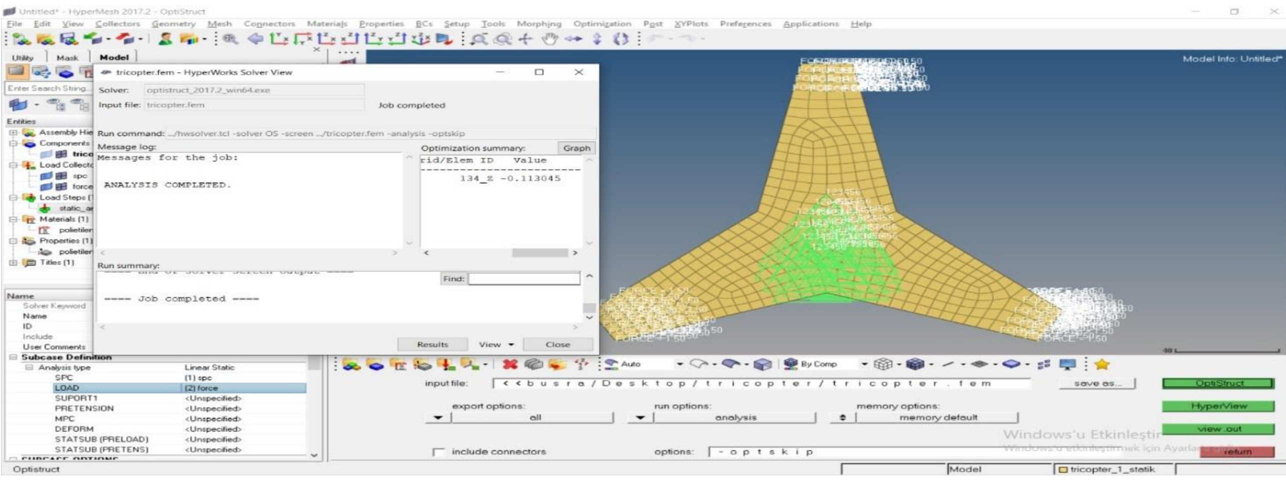


**Figure 4.4.** Analysis properties

The stress values occurring on the part as a result of the static analysis made on the part are shown in the figure below:

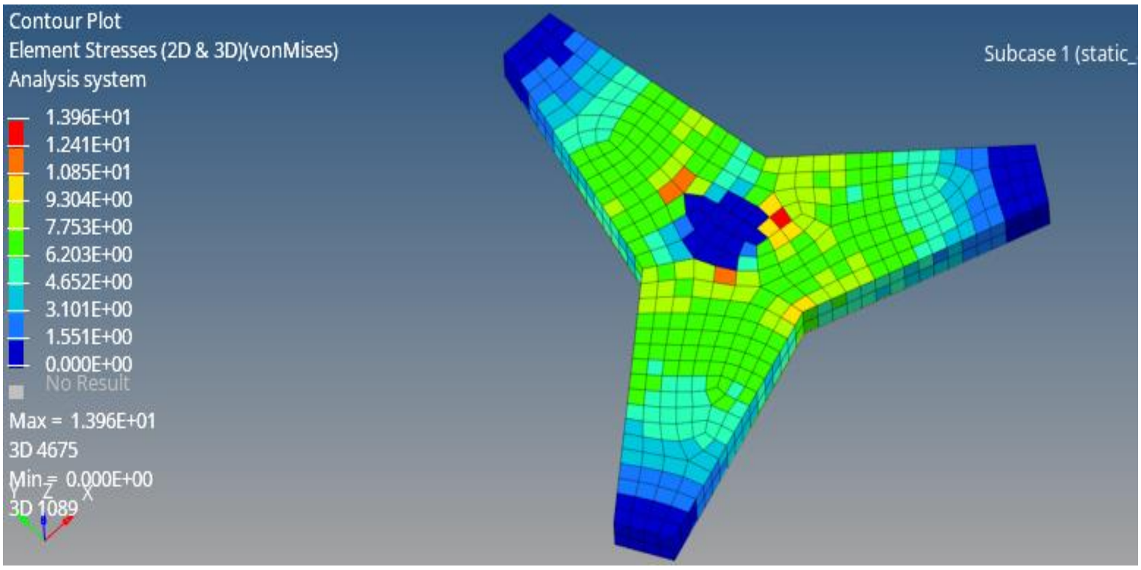


**Figure 4.5.** Von Mises Stresses distribution on the part

The figure below shows the displacement which resulted from the static analysis.

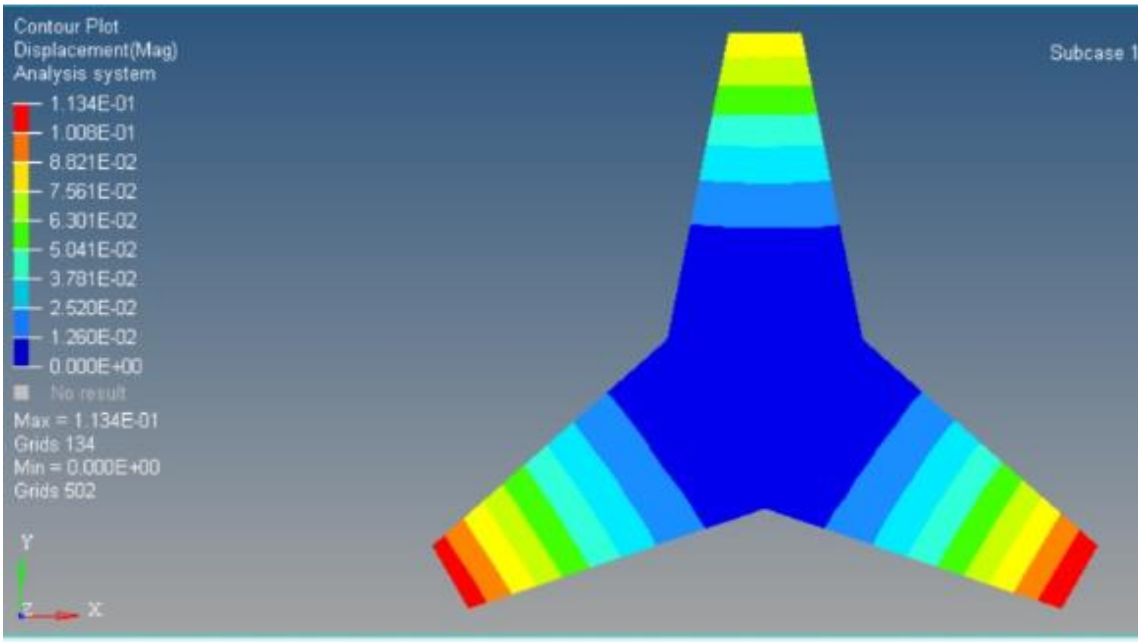


**Figure 4.6.** Displacement distribution on the part

### 4.3 Topology optimization

Topology optimization was carried out using the Altair Optistruct module.

The following flow chart was observed during the optimization process.

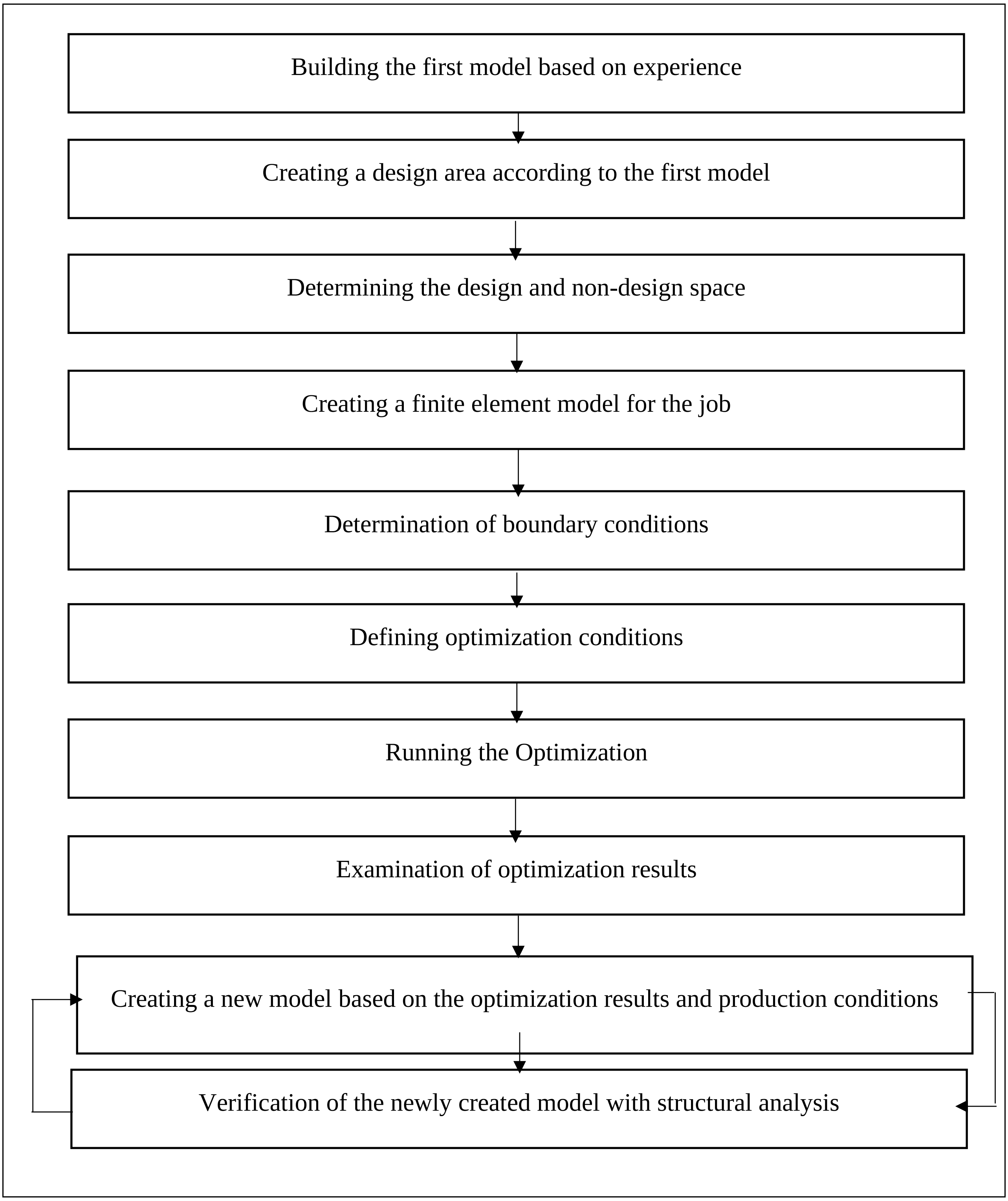


**Figure 4.7.** Topology optimization process

The figure below shows the model that was used in topology optimization. The pink arrows represent the SPC load collectors.

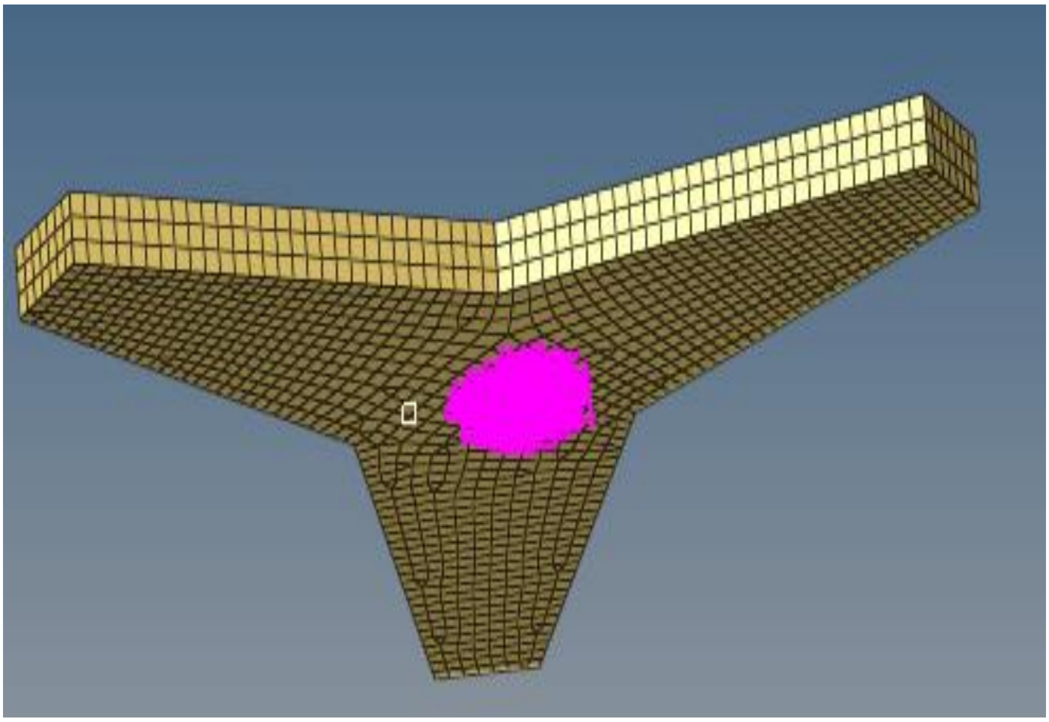

**Figure 4.8.** The model that was used in the topology optimization

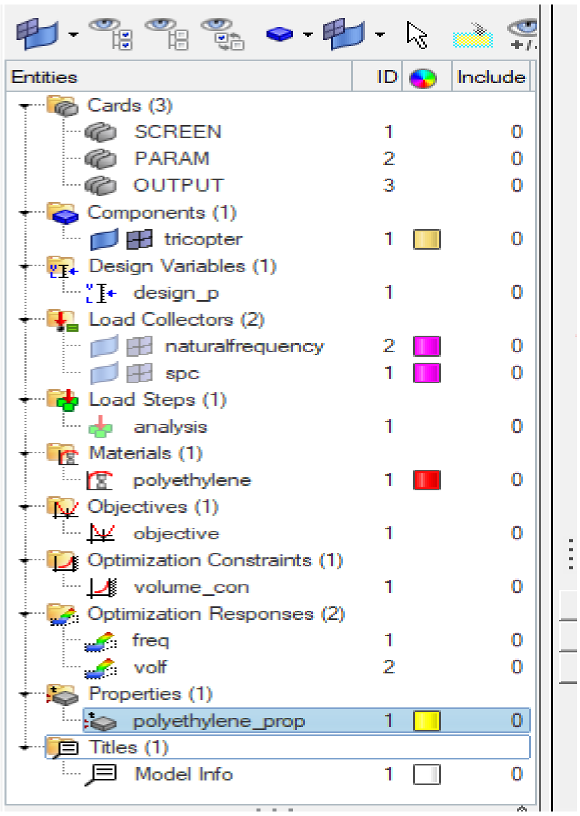


**Figure 4.9.** Topology optimization parameters

After all these processes, topology optimization was done using the Altair Optistruct module. The purpose of this process is to obtain the most suitable model for the desired conditions according to the defined limits.

The figure below shows the Eigen Mode results of the static analysis done.

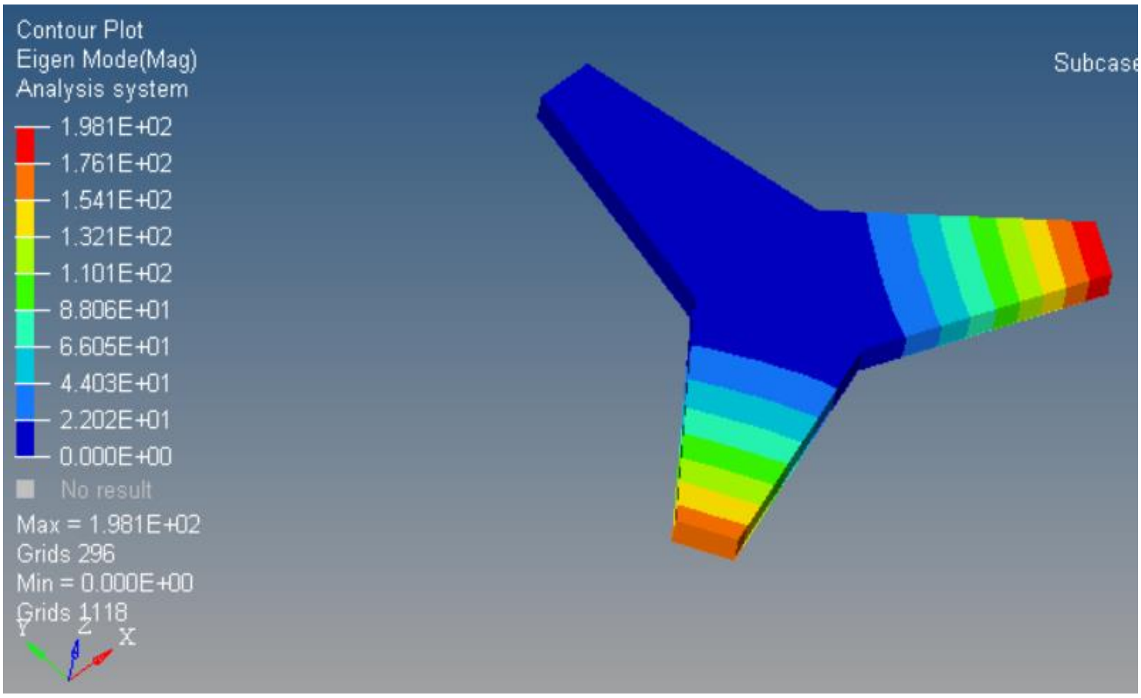


**Figure 4.10.** Analysis result (Eigen Mode)

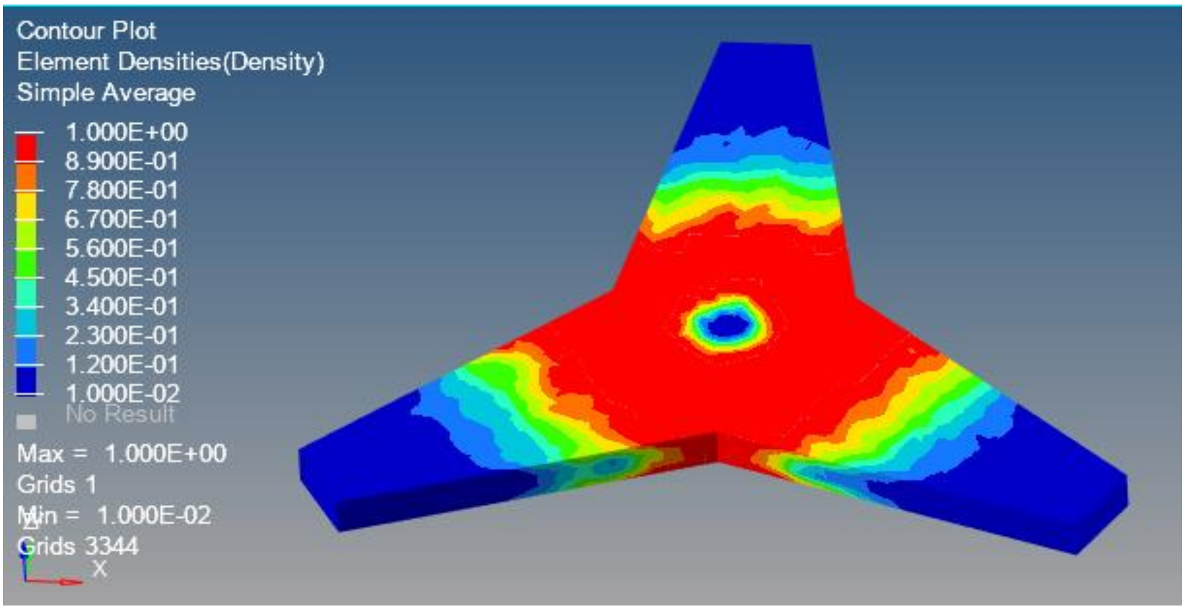


**Figure 4.11.** Topology optimization result

The objective of the optimization was to maximize the frequency and the graph below shows the results.

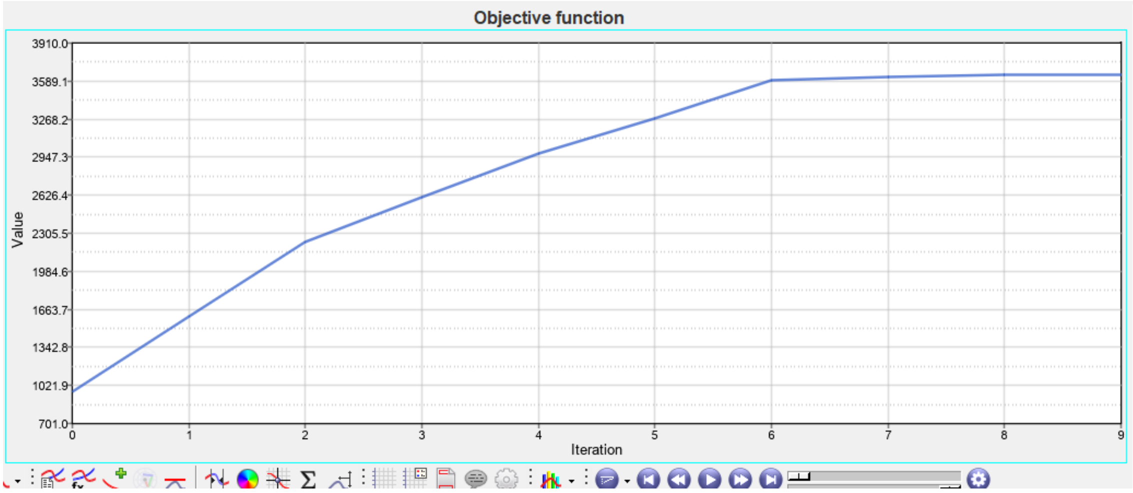


**Figure 4.12.** Objective function plot

### 4.4 Analysis of the New Model

The new model was created on CATIA V5.

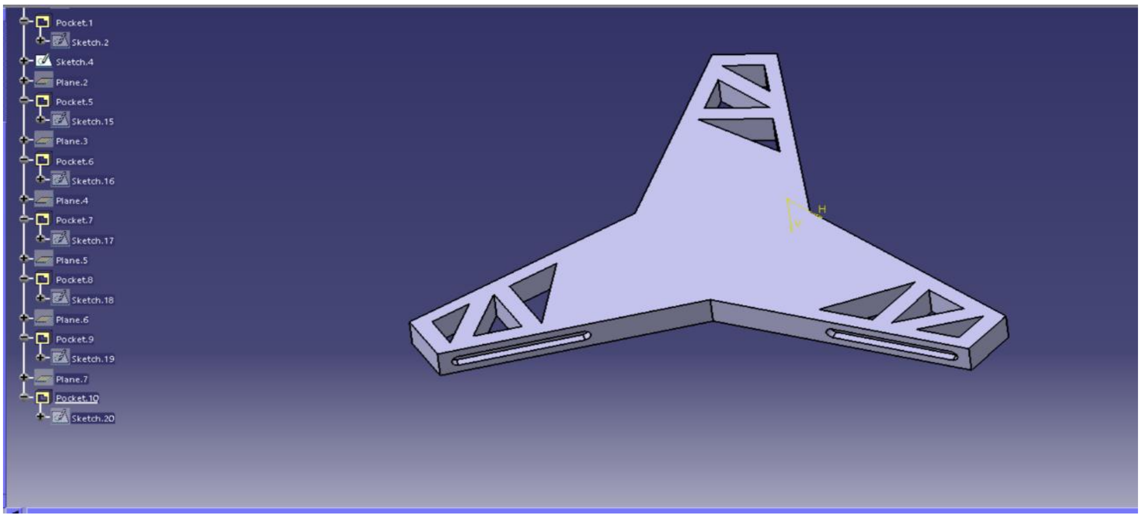


**Figure 4.13.** New Model after Topology

The model was transferred to hypermesh 2019.1. The meshing was done. The material, properties, and components were created and assigned. The force and SPC loads were created, as seen in the figure below. Then the new model was analyzed.

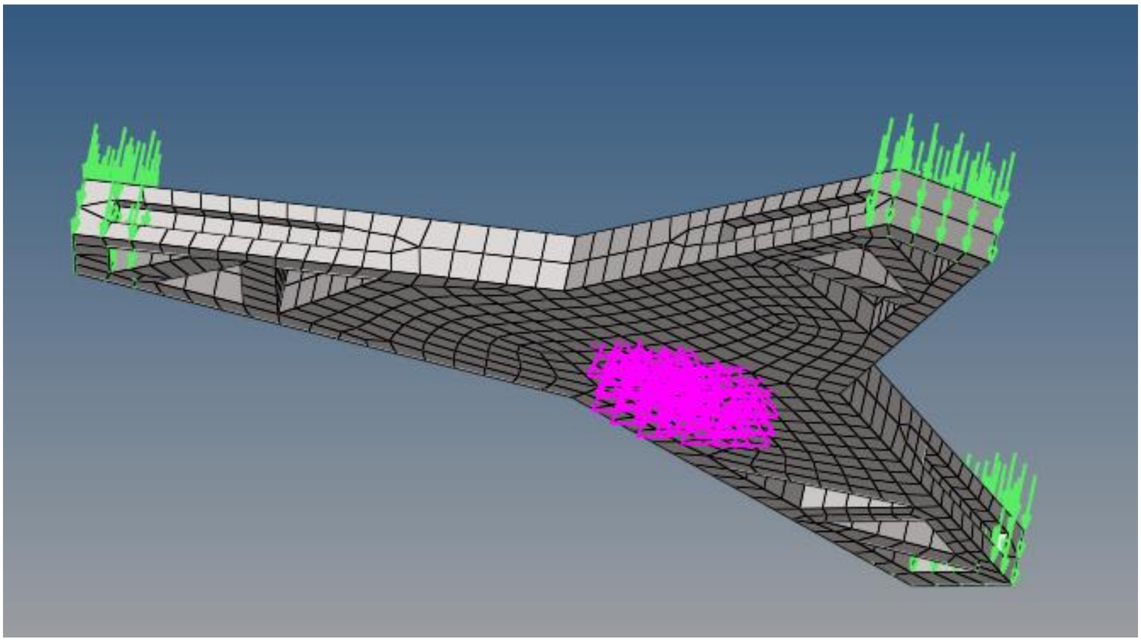

**Figure 4.14.** Meshed model showing load collectors

After successfully running the program, the topology optimization results are shown below.

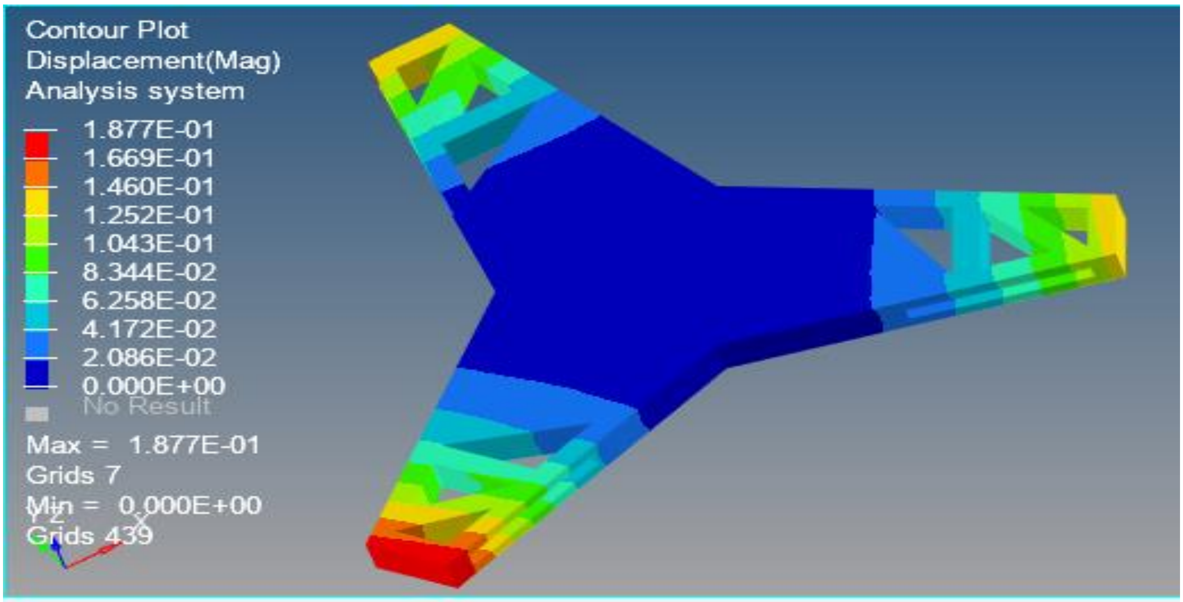

**Figure 4.15.** Displacement distribution of the new model

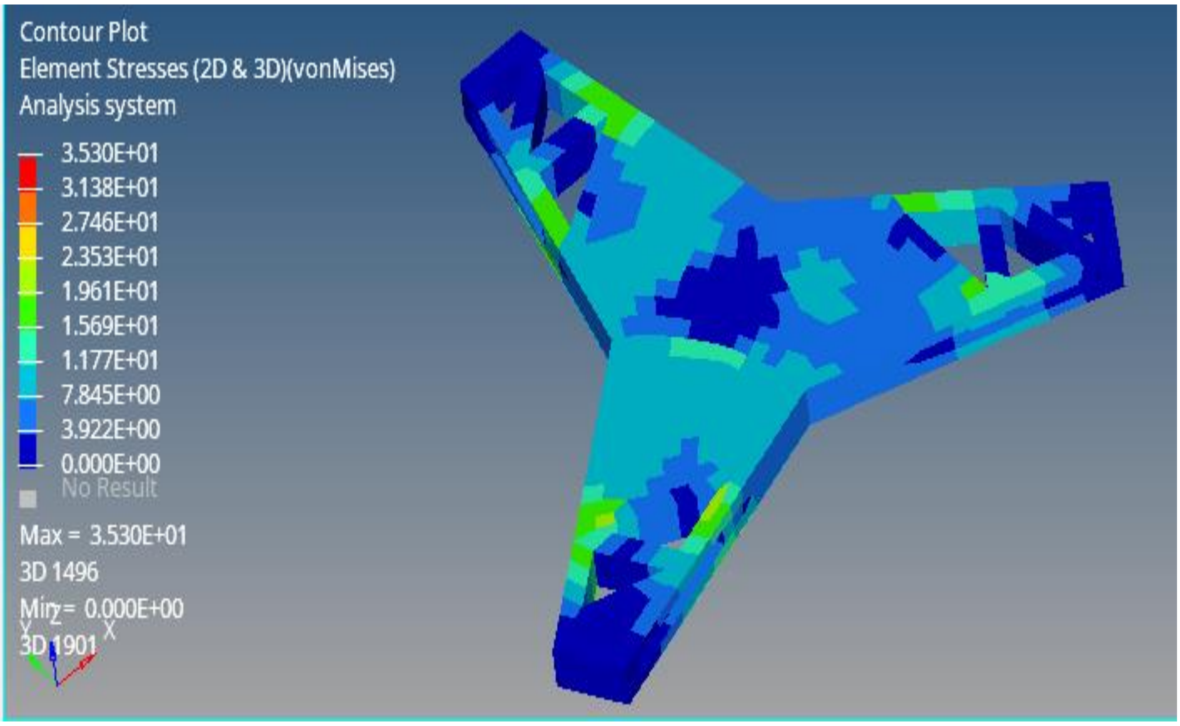


**Figure 4.16.** Von Mises Stresses distribution of the new mode

The results obtained as a result of the analysis and optimizations are given in Table 7.1. The maximum stress increased after topology optimization. As a result of optimizations, the weight has been reduced by 14.96%, while the volume was reduced by 15.5%.

The maximum stress increased by 152%, and the maximum displacement increased by 65.5%.

**Table 4.1** Pre- and post-optimization results

| Model | Mass (kg) | Volume ($m^3$) | Maximum Stress ($N/m^2$) | Maximum Displacement (m) |
|---|---|---|---|---|
| Pre Optimization | 0.127 | 0.000106 | 13.96 | 0.1134 |
| Post Optimization | 0.108 | 0.00008958 | 35.3 | 0.1877 |
| Change | -14.96% | -15.5% | 152% | 65.5% |

## 5. CONCLUSION

Vehicles are the main contributors to carbon dioxide emissions, which are very harmful to the environment. These harmful emissions need to be mitigated, and one of the main ways of doing this is by reducing the weight of our vehicles. Weight reduction of vehicles can also provide significant benefits in fuel savings, which results in cost reduction. Recently, the main target of industries is vehicle lighting, which employs the usage of lighter materials to find optimum values without compromising the strength of the systems. Optimization methods are used to achieve this target.

In this study, structural optimization was made on a tricopter model part. Firstly, the model was created on CATIA V5 and analyzed on Hypermesh 2019.1. Then the model was optimized using topology optimization techniques. As a result, the mass of the model decreased by 14.96%. Therefore, the aim of our studies is achieved.

From this study, it can be deduced that more durable parts can be produced by using optimization methods.

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**RESUME**

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