Celal Bayar University Journal of Science

A Study on Topology Optimization of Landing Gear Parts

Sait Cumhur Pıçak[1]*, Mehmet Yahşi[1], Erol Gültekin[2]

[1] Turkish Aerospace Industries Inc. (TAI), Ankara, Türkiye
[2] Department of Mechanical Engineering, Faculty of Engineering, University of Turkish Aeronautical Association, Ankara, Türkiye
* saitcumhur.picak@tai.com.tr
* Orcid No: 0009-0000-6809-7230

Received: 26 August 2024
Accepted: 4 December 2024
DOI: 10.18466/cbayarfbe.1539030

Abstract

In the aviation industry, one of the most complex industries in the world, the importance of low-weight design of aircraft is increasing day by day. While the requirements and related regulations regarding the efficient use of energy and minimizing environmental impacts are increasingly included in the legal framework, the importance of designing aircraft with low weight and therefore advantageous in terms of fuel consumption in the aviation sector, where competition is quite intense, is also increasing rapidly day by day. As a result of this situation, structural and parametric optimization, especially topology optimization studies, for the design of aircraft components with low weight, emerge as an indispensable element of design processes in the aviation industry. In this study, a Torque link and Trunnion landing gear parts were used. Firstly, the topology optimization study is performed as one conditional with separated two load cases. Afterward, the multi-conditional topology optimization is done with the aforementioned load cases. A weighted compliance parameter is generated to use in multi-conditional optimizations as a constraint or objective. While generating weighted compliance value, proportional weighted compliance (PWC) method is compared to the equal-effect weighted compliance (EEWC) method. With the EEWC method, on the torque link parts, 43% volume fraction is achieved and 34% volume fraction is obtained with the PWC method. Similar study has been done once again with landing gear Trunnion part and there were seen that the PWC method is a more effective approach in multi-conditional topology optimizations.

Keywords: Finite Element Analysis, Landing Gear, Topology Optimization

1. Introduction

As is well known, aircraft perform their flight missions by working against gravity. Therefore, the less load exerted on the propulsion components of the aircraft, the lower the fuel consumption will be, and it will be more advantageous in terms of strategic missions. At the same time, the lighter the structural parts of the vehicle such as its body and engine, the more the useful load (passengers, cargo, or ammunition in military vehicles) the aircraft can carry will increase accordingly, making the use of the aircraft in this manner quite important. Hence, one of the most important research areas of material science and technology is the aviation industry. It is observed that the efforts to lighten aircraft components are more focused on material solutions [1]. In this study, the focus is on redesigning the part through topology optimization without changing the material. In a study conducted by Raicevic et al. [2], the fatigue life of a damaged torque link was analyzed, a suitable material was identified for additive manufacturing, residual stresses from production were included, and new torque link designs were obtained through analysis-optimization studies, providing an alternative design method in the design processes. In a study conducted by Srinivas and Javed [3], the optimum design of robotic arms was studied. Instead of optimizing according to the loading conditions at the time step of the worst load scenario, which is commonly used in the topology optimization of dynamically working parts, the aim was to obtain an optimal material distribution for each condition by using designs obtained from optimizations under different positions and loading conditions. In an analysis study conducted by Infante et al. [7], a finite element analysis (FEA) of a fork part in the front landing gear of an aircraft was performed. The part analyzed was damaged during flight operations. It was found that the regions critical in the stress analysis were in close proximity to the physically damaged regions on the part. In a FEA study conducted by Freitas et al. [8], a stress analysis of an axle part of an aircraft was carried out. The part analyzed was found to be damaged during flight. Observations on the damaged physical part revealed that an overload situation caused the damage. The FEA studies also indicated a high probability of damage under the same conditions. In a study conducted by Bagnoli et al. [9], the damage to a swing arm part in the landing gear of a civil aircraft was examined. Irregularities originating from manufacturing were found in the internal structure of the part examined after the fracture, and it was concluded that the damage was a fatigue failure resulting from repeated loadings. The FEA studies also identified stress concentrations in the damaged region. A paper submitted by Gu et al. [12] introduces a pioneering method termed nonlinear fatigue damage constrained topology optimization. The method integrates several key components: the rainflow counting method to evaluate the non-proportional cyclic load levels, Basquin's equation to describe the S-N curve, and Morrow's plastic work interaction rule to calculate the nonlinear cumulative damage of the structure. They established a mathematical model for the nonlinear fatigue damage constrained topology optimization method based on the components. In a paper submitted by Song et al. [15], the appearance of sharp 'V' features at joint areas in multi-material topology optimization, originating from independent minimum length scale control is delved. The modified minimum length scale controls for multi-material problems are proposed based on geometric constraints and the indicator functions with a normalization gradient norm. The results indicate that the combinations of two minimum length scale controls cannot achieve the parallel distribution and wrapped distribution due to the limited ability to modify the material layout. A paper submitted by Dong et al. [32] presents a topology optimization framework based on the bi-directional evolutionary structural optimization (BESO) method for designing SMA structures, which maximizes structural stiffness under multiple constraints of specified volume fraction, displacement, and fundamental frequency. Several optimized SMA beam structures and simply-supported cube structures are designed under different thermal-mechanical loads, and their displacement, mean compliance, and fundamental frequency are evaluated throughout the optimization process. The results demonstrate that the proposed framework successfully customizes the SMA topology structure with adjustable displacement and fundamental frequency, and the optimized schemes exhibit more considerable deformation and more uniform mechanical properties than their initial counterparts. In order to use topological optimization results in final product designs without too much effort, DDM(Direct Digital Manufacturing) is an important technology that has persisted from the past to the present. Complex geometrical structures with light weight are the greatest interest of the aerospace, spacecraft, and automobile industries. A study conducted by Patham K.F. [33] aims to explore the possibilities of implementing DDM for small and medium manufacturing firms by combining the advances of computer application software, topology optimization, and additive manufacturing. The results indicated that that redesign was an efficient method for producing lightweight aerospace structures and components without using expensive novel lightweight materials. A paper submitted by Tang et al. [34] proposes a multi-objective topology optimization method combining Analytic Hierarchy Process (AHP) and topology optimization. A comparison of the comprehensive performance of the frame before and after optimization shows that the proposed method enables the optimized frame to meet the strength requirements under various working conditions, resulting in a weight reduction of 16.5 kg. Crash topology optimization is a typical nonlinear dynamic response structural topology optimization problem, which is one of the most difficult problem in the structural design field. The equivalent static load method (ESLM) provides a well-defined pattern to solve such difficult problems, which can convert a nonlinear dynamic response optimization into multi-load steps optimization problem with the equivalent static loads (ESLs). In a study conducted by Ren et al. [35], to expand the application scope of the ESLM, an improved ESLs calculation method is proposed by using the model order reduction method and energy principle, which only acting on some nodes and can be scaled adaptively. The results show that, the proposed method can effectively solve the crash topology optimization of thin-walled structures under large deformation crash condition. As urbanization continues to accelerate, dump trucks assume an increasingly important role in the transportation and construction of infrastructure. One of the primary failure modes of the carriage is weld fatigue failure, which frequently gives rise to the problem of weld fatigue cracking during transportation. To increase the fatigue life of welds and enhance the degree of structural lightweight of a heavy dump truck carriage, a method for anti-fatigue lightweight design based on machine learning and multi-objective optimization is proposed by Lan et al. [36] and the proposed design method achieves a good effect in the anti-fatigue lightweight of dump truck carriage. Traditional residential timber frames, embodying centuries of Chinese craftsmanship, continue to thrive. To determine the optimal design dimensions for these frames, a study conducted by Yuanyao et al. [37] introduces a combined optimization approach using Response Surface Methodology (RSM) and Multi-Objective Genetic Algorithm (MOGA). Using the Optimal Space-Filling (OSF) method, sample points within the design domain were collected to establish a response surface model, correlating frame dimensions with key structural metrics: maximum deformation, maximum Mises stress, and total mass. The findings of the study provide valuable insights for related

Celal Bayar University Journal of Science
Volume 21, Issue 2, 2025, p 35-46
Doi: 10.18466/cbayarfbe.1539030

engineering applications and a calculation model for the fatigue damage degree of concrete was proposed. In a paper submitted by Wang et al. [38], the lightweight design of the automotive front subframe was performed by combining multi-condition topology optimization and multi-objective optimization approaches. Multi-condition topology optimization of the front subframe envelope was performed utilizing the compromise programming approach. The optimized front subframe has met various performance specifications while increasing the first-order frequency by 10 Hz and reducing weight by 3.27 kg. In addition to the well-developed topology optimization (TO) method, structural bionics is also considered an effective approach to developing innovative structure designs with lightweight. In the process of natural evolution, bamboo has developed a unique hollow structure with ingenious mechanical properties. Inspired by these characteristics, a paper submitted by Zhu et al. [39] selected bamboo as a bionic prototype to carry out bionic structure optimization of guide arm. According to the results, under the premise of the mass of the optimized bionic model decreased by 17.44%, the maximum deformation was decreased by 9.24%, the equivalent stress was decreased by 17.33%, and the first-order frequency was increased by 22.92%. Comparison results showed that the proposed bionic model provided the best lightweight solution for guide arm. A paper conducted by Chen et al. [40] presents a comprehensive optimization design method for composite materials in order to investigate the impact of the coupling effects of carbon fiber reinforced polymer in the seat back layer on the performance of car seats. The results show that ensuring the safety performance, the total mass of the seat backrest decreased by 21.3%, as a result of the optimization strategy proposed in this paper, and the comfort performance is also improved to some extent. Sandwich structures with lattice cores are novel, lightweight composite structures and are widely used in the aerospace industry. A study conducted by Najafi et al. [41] investigates the supersonic flutter of a sandwich panel whose core is topology-optimized. The modeling approach is fully validated, and the results demonstrate that the sandwich panel is capable of enlarging the flutter-free operational flight range when compared with other conventional panel designs. Development and evaluation of a novel design of mass reduced aircraft wing ribs through topology optimization is reported in a paper submitted by Rahman et al. [42]. Methodology in this study includes the k-Ω shear stress transport turbulence model computational fluid dynamic simulation as well as static and transient finite element simulations. The optimized wing rib is found to be between 8% and 15% lighter than traditional wing ribs depending on configuration.

A substantial amount of numerical studies are performed in topology optimization field. It has been an important purpose that reduce the weight or increase the stiffness of the structure. In a classical topology optimization problem, reducing the volume of the part is aimed. Remaining constant or minimizing the compliance (total strain energy) output is often used to save the stiffness of the structure since reducing the volume will cause the reducing stiffness. In problems involving multiple loadsteps, naturally, as many compliance values are obtained as the number of loadsteps. In a single-objective optimization problem, these values need to be aggregated in some way to obtain a new value that can be minimized. In this study, performance of two methods were used to obtain total compliance value. EEWC (equal-effect weighted compliance) method gets the total compliance value by directly summing the compliances of each loadsteps. PWC (proportional weighted compliance) method calculates the total compliance value by multiplying each compliances with some weight factors and finally summing them. These factors are calculated by proportioning. In our study, in order to obtain weight-effective structures, these two methods were operated and the results were compared.

2. Materials and Methods

Structural optimization studies can also be divided into two groups: "concept design" and "fine-tuning." In concept design studies, the design concept of the structural design is not known at the beginning of the study. Typically, a bulk structure is created that fills the entire design space allowed for the design, and a design topology meeting the desired objectives and constraints is obtained from this structure through topology optimization. Examples of other concept design studies include topography optimization and free-shape optimization. In topography optimization, the aim is usually to achieve high strength and high natural frequency values by creating bead structures on a shell structure with a certain thickness. In free-shape optimization, certain surfaces of a three-dimensional model are defined as free-shape surfaces, and the forms these surfaces take as a result of optimization are reflected in the design. In fine-tuning studies, there is a pre-defined design at the beginning, either previously obtained as a concept design or formed through an initial assumption, experience, etc. The aim in fine-tuning studies is to obtain the optimum geometry of this defined design. For this purpose, geometric parameters such as radius, thickness, hole diameter, etc., are defined as design variables. Additionally, shape parameters obtained by mesh morphing in the finite element model can also be defined. In addition to these structural optimization studies, parametric optimization studies that only process numerical inputs and outputs are also frequently encountered. In these studies, after defining the input parameters called design variables, a design of experiments can be performed to determine which change in the input parameters highly affects the examined output parameters, and in the next step, to

avoid processing clutter, the optimization process can be applied considering only these parameters. Again, in parametric analysis studies, if long analysis tools are used to obtain outputs at each iteration, an appropriate mathematical model can be created using a data set containing the outputs obtained for specific inputs. Thus, instead of lengthy analysis processes at each step, the outputs generated by this mathematical model can be used by the optimization software, allowing for faster attainment of extremum values with an acceptable error margin.
Topology optimization is a significant tool in order to get proper designs from concept stage. Classical topology optimization cycle can be seen in Figure 1.

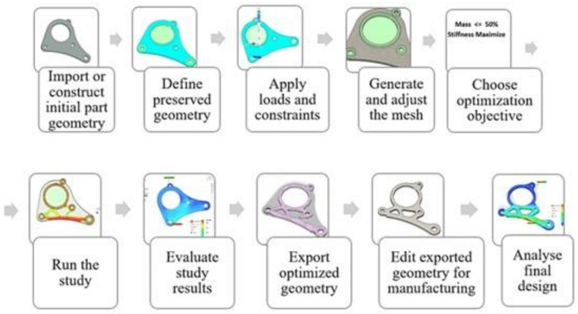

Figure 1. Topology optimization steps [24]

In this study, commercial finite element and optimization solver OptiStruct is used in order to perform FEA and topology optimizations. OptiStruct uses one of the gradient based optimization algorithms called Enhanced Dual Optimizer based on separable convex approximation (DUAL2) [25]. As with all other types of optimization; in order to build a topology optimization problem, three fundamental arguments are needed to form a structural optimization problem. These arguments are design variables, constraints, and objective parameters. Design variables are the parameters that will be modified throughout the optimization iterations. By continuously assigning new values to these parameters according to an appropriate algorithm, an optimum design is sought. In topology optimization, the material density of each element is directly used as the design variable and varies continuously between 0 and 1; these represent the state of void and solid, respectively. Intermediate values of density represent fictitious material. The stiffness of the material is assumed to be linearly dependent on the density. This material formulation is consistent with our understanding of common materials. For example, steel, which is denser than aluminum, is stiffer than aluminum. Following this logic, the representation of fictitious material at intermediate densities does reflect engineering intuitions.
Then it is required to define responses. Optistruct allows the use of numerous structural responses, calculated in a FEA, or combinations of these responses to be used as objective and constraint functions in a structural optimization. Constraints and objective functions use the outputs at each iteration in the optimization process. Depending on the algorithm or analysis used as the iteration step, these outputs can be very different parameters. For instance, in a structural analysis, the outputs can be general FEA parameters such as stress, displacement, etc., or parameters calculated by the software to be used in the iterations, such as mass, volume, etc., which the software is instructed to modify. Constraint parameters are those defined as lower or upper limits, or optionally both, for the numerical values of these outputs. During each iteration, the optimization algorithm checks whether the constrained outputs remain within the defined lower or upper limits. Reaching the optimum result is possible when the constrained outputs stay within the limit values or exceed the limits by a predefined allowable percentage. The objective function aims to minimize or maximize a selected output parameter. Additionally, it is possible to define an objective function to minimize the maximum value or maximize the minimum value of a set of output parameters. While multiple constraint functions can be defined, the objective function is singular. However, multi-objective optimization processes have also been developed in recent years. Generally, in structural optimization studies, the aim is to minimize mass or maximize stiffness.

One of the important responses generated by the solver is “Static Compliance”. In mechanics, compliance" means inverse of "stiffness". To improve the structural integrity it is often necessary to minimize the strains in the structure which means minimizing the compliance or maximizing the stiffness. The compliance C is calculated using the following relationship [29]:

$$C = \frac{|x|}{|f|} \tag{1}$$

Where $|x|$ is the magnitude of applied force and $|f|$ is the magnitude of the displacement.

In this study, weighted compliance output is also used. The weighted compliance is a method used to consider multiple subcases (loadsteps, load cases) in a classical topology optimization. Each compliance value produced for the respective load step is multiplied by a weighting factor, and the results are summed up. The response is the weighted sum of the compliance of each individual subcase (loadstep, load case).

$$C_{total} = \sum_{i=1}^{n} w_i c_i \tag{2}$$

where:

- C_{total}: Total weighted compliance.
- w_i: Weighting factor for load case *i*.
- C_i: Compliance (strain energy) for load case *i*.

- *n*: Number of load cases.

This is a global response that is defined for the whole structure.

In this study, topology optimization study is performed on landing gear parts. During landing and ground operations, landing gear is the most critical system of the aircraft. It provides a ground support, energy absorption during landing and load connection between body(fuselage) and ground plane. In smaller aircrafts, generally a lip spring including landing gear are used. In bulkier aircrafts, pneumatic and oleo-pneumatic type of landing gears are generally used. Landing gears meant for their large ‘‘safe life” segments along with that they are supplanted ordinarily while the administration life of an airplane [27].

In Figure 2, it can be seen a landing gear model and its important parts.

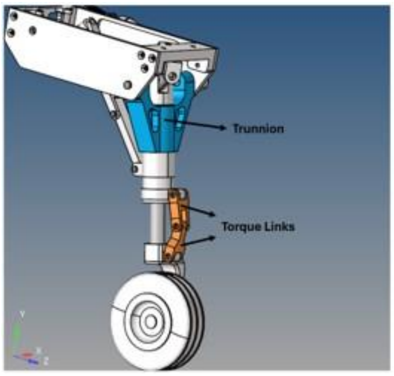

Figure 2. Landing gear model [30]

Landing gear is, by its nature, dynamic equipment that counters not only the loads applied by the aircraft and the ground but also the aerodynamic and inertia loads during deployment and retraction [10]. In a typical aircraft, the landing gear is usually characterized by two masses, a spring, and a damper. The schematic representation of this design can be seen in Figure 3.

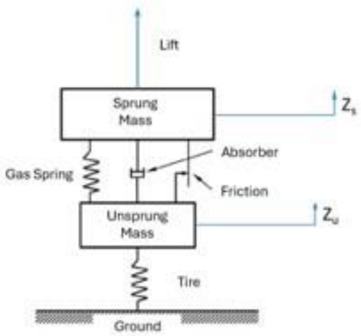

Figure 3. Schematic representation of a single landing gear [10]

A set of loads is determined for the landing gear according to the specified operation scenario. Under the conditions of this load set, the landing gear is expected to have sufficient structural strength. The load set is generally defined as load components in the Cartesian coordinate system at the tire contact points of the landing gear and the landing gear must not suffer damage when these load components are statically applied. The parameters affecting this static strength condition include the applied load conditions, the geometry of the landing gear components, and material characteristics. Most of the static loads applied are defined as "limit loads." Limit loads are considered the highest load conditions the landing gear may encounter during operation. The static strength of the landing gear must be sufficient to prevent permanent deformation when exposed to any of these limit loads. Additionally, to ensure an extra safety condition, strength calculations for the landing gear are also performed for maximum loads obtained by multiplying the limit loads by 1.5 [31]. However, at this level of load conditions, permanent deformation is allowed on the landing gear, provided that structural integrity is not compromised. To meet this requirement, the stresses obtained as a result of maximum loading are compared with the ultimate strength of the landing gear materials.

Initially, two critical load conditions will be included individually in the optimization study. Subsequently, an examination will be conducted using a method where the effect of these loads on the structure is evaluated together. One of the most important parameters used in measuring the structural strength of industrial designs is the output parameter called "compliance" obtained as a result of strength analyses. This value is equivalent to the total strain energy absorbed by the structural system, and high values indicate low rigidity of the structure. Therefore, the objective function in optimization studies is generally defined to minimize this value, i.e., to maximize the stiffness (rigidity) value. In finite element models, a different analysis step (Loadstep) can be defined for each loading condition, allowing for comparison of the effects of different loading conditions on the structure within a single computer-aided engineering analysis. Additionally, different categories of loading conditions such as gravity can be defined once and combined with other analysis steps. In FEA models with multiple loading conditions, the issue of which loading condition to use for the optimization process can become complex. To easily overcome this complexity, a "weighted compliance" value obtained by multiplying the compliance value of each loading condition by a specific coefficient and summing the new compliance values derived from all conditions can be used in optimization software. This value is also automatically provided to the user at the parameter selection stage in most structural optimization software. In this study, a finite element model of a torque link part

has been created, and the design space has been determined.
In the created model, the number of nodes used is 39,016 and the number of elements is 200,631. The finite element model and the design space allocated for optimization can be seen in Figure 4.

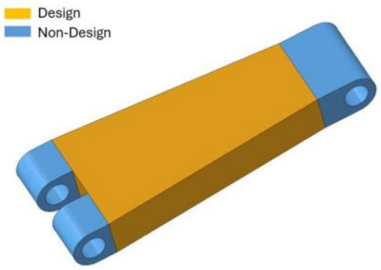

Figure 4. Finite element model and design space of the torque link

Landing gears generally use oleo-pneumatic suspension systems containing gas-fluid to absorb the ground reaction force generated during landing. Unlike automotive axle systems, these systems usually do not use axle systems for installation, and instead of restricting the rotational movement of the wheels by shape, external torque links are used. Torque links are components that prevent the wheels from rotating around their own axes or a certain axis. Therefore, the torque link part shown in Figure 2 is continuously subjected to bending effects during ground maneuvers. The first loading condition to be used in the optimization phase in this study is based on this bending effect. To simulate the torsional effect that may occur on the torque link due to deformation of other landing gear parts such as the axle, and to obtain a different loading scenario as an optimization method, a torsional moment was applied to the torque link as the second condition. The schematic representation of the applied loading scenarios can be seen in Figure 5. In the bending scenario, a force of 45 kN was applied to the torque link connection point. In the second scenario, a torsional moment of 2500 Nm was applied. These loading values correspond to the ground loads of the landing gear of a lightweight aircraft.

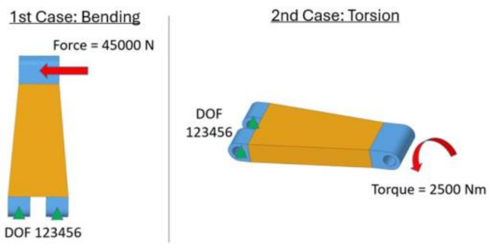

Figure 5. Loading and boundary conditions

The material of the torque link examined in the study is Ti6Al4V alloy. The mechanical properties of the material are given in the table below:

Table 1. Ti6Al4V Material Properties [5]

Modulus of Elasticity [MPa]	Poisson Ratio	Yield Strength [MPa]	Ultimate Tensile Strength [MPa]
113800	0.342	790	860

In topology optimization applications, the aim is generally to obtain the most robust design with the lightest weight [28]. In this study, the first analysis output to be used in the optimization problem is the volume fraction. This value is calculated as the ratio of the volume of the design space after optimization to the initial volume. The other output is the compliance, which is interpreted as the inverse of the stiffness of the structure and represents the total strain energy. The higher the compliance value, the lower the stiffness of the structure. In this study, while defining the optimization problem, a compliance value of 120 Nm was set as the upper limit to form the constraint function, and the volume fraction was defined as the objective function to be minimized.

For multi-conditional topology optimizations, two methods for defining weighted compliance are compared. The coefficients are used to multiply the compliance values which separately produced by unique load cases. If we define these compliance values C_1 and C_2, the formula (4) becomes:

$$C_W = W_1 C_1 + W_2 C_2 \quad (3)$$

where W_1 and W_2 are the coefficients called "weight factors" multiplied with the compliances in order to generate weighted compliance value C_W. In the Equal-Effect Weighted Compliance (EEWC) method, these coefficients are set as the same and equal to 1. Therefore (5) formula becomes:

$$C_W = C_1 + C_2 \quad (4)$$

$$W_1 = W_2 = 1 \quad (5)$$

In the Proportional Weighted Compliance (PWC) method, compliance values C_1 and C_2 are calculated once. For instance, consider the following example: $C_1 > C_2$. Therefore, W_1 coefficient is set to 1 and W_2 coefficient is calculated as below:

$$W_2 = \frac{C_2}{C_1} \quad (6)$$

$$C_1 > C_2$$

$$W_1 = 1$$

Celal Bayar University Journal of Science
Volume 21, Issue 2, 2025, p 35-46
Doi: 10.18466/cbayarfbe.1539030

Therefore, the weighted compliance value C_W is calculated as:

$$C_W = C_1 + \frac{C_2}{C_1} C_2 \quad (7)$$

3. Results and Discussion

The study results consist of two section considering the Torque link and the Trunnion. Topology optimization analyses of the Torque link were presented as four separate studies while for the Trunnion, the analyses were completed using EEWC and PWC methods.

3.1 Topology Optimization of Torque Link

Topology optimization analyses of the Torque link were defined according to the bending condition, the torsion condition, the third condition where both conditions have equal influence, and the fourth condition where each condition has an effect proportional to its own compliance value.

3.1.1. Topology Optimization with Bending Condition

The material distribution results according to the first condition, the bending condition, are shown in Figure 6. The optimal model was obtained after 30 iterations.

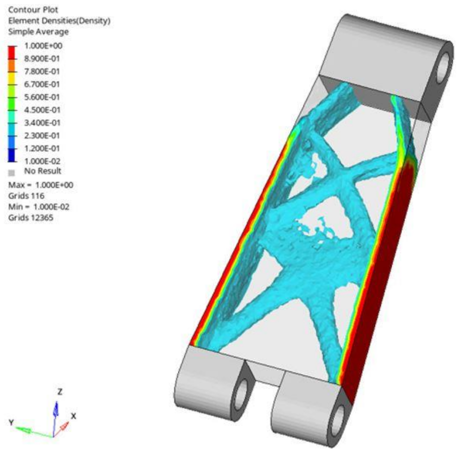

Figure 6. Topology optimization result of bending condition

In this optimization, the volume fraction value to be minimized was obtained as 0.17 for the optimal model. The compliance value is 119.5 Nm, which satisfies the upper limit constraint of 120 Nm.

3.1.2. Topology Optimization with Torsion Condition

The material distribution results according to the second condition, the torsion condition, are shown in Figure 7. The optimal model was obtained after 15 iterations. A longitudinal section view has been added to provide a clearer view of the material distribution.

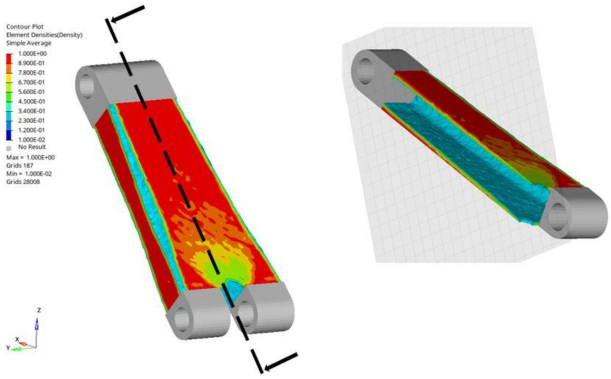

Figure 7. Topology optimization result of torsion condition

The volume fraction value to be minimized was obtained as 0.26, and the compliance value is 119.8 Nm, which satisfies the upper limit constraint of 120 Nm.

3.1.3. Topology Optimization with the EEWC Method

In the optimization study defined as the third condition, the compliance value uses the weighted compliance output, calculated by taking the sum of the compliance values obtained from analyzing both conditions. This value has been defined as a constraint, as in the first two optimization studies. The material distribution results according to the EEWC method are shown in Figure 8. The optimal model was obtained after 12 iterations. A longitudinal section view has been added to provide a clearer view of the material distribution.

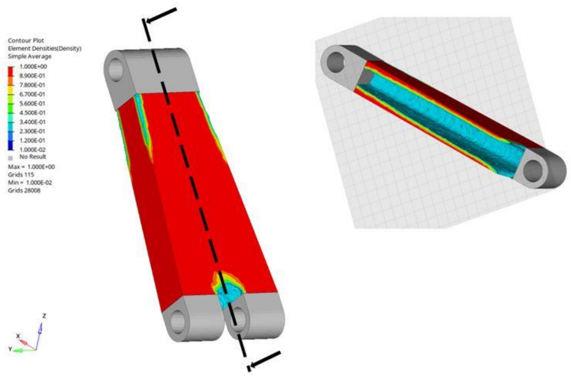

Figure 8. Topology optimization result of EEWC Method

The volume fraction value to be minimized was obtained as 0.43, and the compliance value is 119.98

Celal Bayar University Journal of Science
Volume 21, Issue 2, 2025, p 35-46
Doi: 10.18466/cbayarfbe.1539030

Nm, which satisfies the upper limit constraint of 120 Nm.

3.1.4. Topology Optimization with PWC Method

In the optimization study defined as the fourth condition, the weighted compliance output is calculated using the ratio of the compliance values obtained for Weighted each loading scenario. The compliance values obtained in the first iteration of the initial design are 30.57 Nm for bending and 57.191 Nm for torsion. Therefore, the coefficient to be used for the bending compliance in the weighted compliance calculation is 0.53 according to Formula (7), which is the ratio of these two values. The material distribution results according to the PWC method are shown in Figure 9 with a longitudinal section. The optimal model was obtained after 14 iterations.

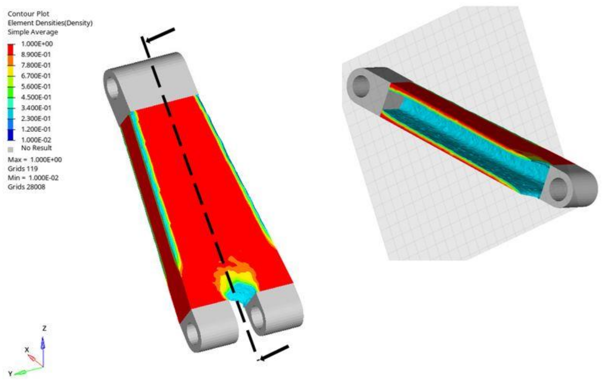

Figure 9. Topology optimization result of PWC Method

The volume fraction value to be minimized was obtained as 0.34, and the compliance value is 119.9 Nm, which satisfies the upper limit constraint of 120 Nm. The outputs obtained from the optimization studies are given in Table 2.

Table 2. Results of Topology Optimizations

Condition	Topology Optimization Method	Compliance [Nm]	Volume Fraction [%]
One Conditional	Bending	119.5	17
	Torsion	119.8	26
Multi Conditional	EEWC	119.9	43
	PWC	119.9	34

When the results on Table 2 were examined, there were seen that the PWC method has more effective results regarding volume fraction for multi-conditional optimizations. The PWC and EEWC methods are compared in another topology optimization study in the next section.

3.2 Topology Optimization Study of Landing Gear Trunnion

The weighted compliance methods EEWC and PWC used on the torque link rod, both were similarly applied to perform topology optimization on a landing gear trunnion component. This part was subjected to finite element stress analysis under two different loading conditions, similar to the previous study. The analyzed component as bulk model is shown in Figure 10.

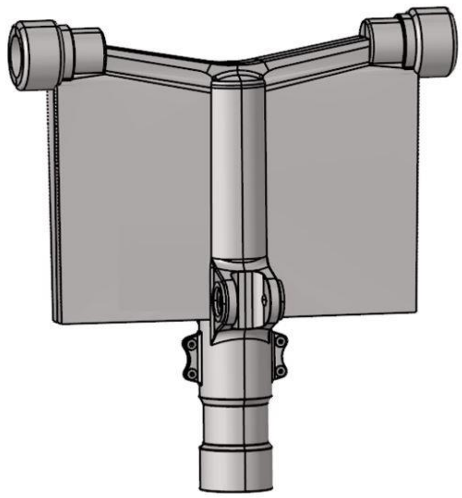

Figure 10. Landing Gear Trunnion Bulk Model

The structural strength of the trunnion component was examined under two different loading conditions. The first condition is the ground reaction force occurring during a vertical landing. The second condition occurs as a result of the horizontal force generated while the aircraft moves forward on the ground. The landing gear trunnion component must be designed to withstand both loading conditions without damage. The visual representation of the loading and boundary conditions is shown in Figure 11. The finite element model consists of 1445534 elements and 286579 nodes. This part has the same material as the first study Ti6Al4V.

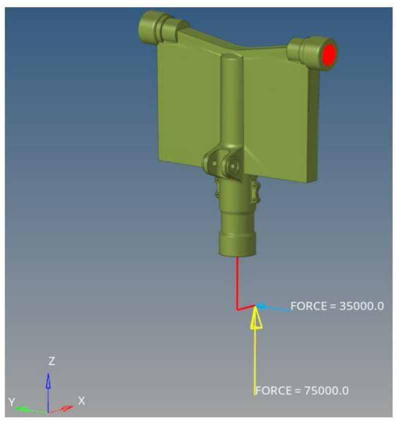

Figure 11. Trunnion loading and boundary conditions

vertical force as 75000 N and horizontal (drag) force as 35000 N are applied to axle center location of landing gear. Initially, bulk model of Trunnion was analyzed regarding both vertical and drag forces. Displacement and stress results of the Trunnion bulk model according to vertical force condition are shown in Figure 12.

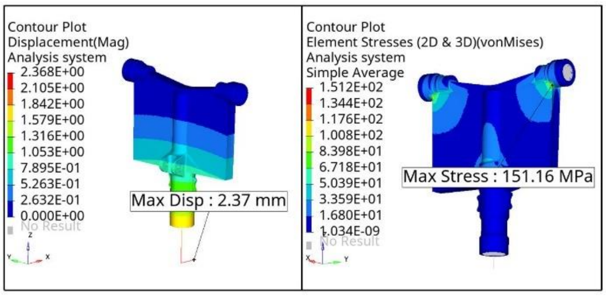

Figure 12. Vertical force displacement and stress results of bulk Trunnion

The stress analysis results of bulk Trunnion according to vertical force condition indicate a maximum displacement of 2.37 mm and a maximum Von Mises stress of 151.16 MPa.

The displacement and stress results of the bulk Trunnion according to drag force condition are shown in Figure 13.

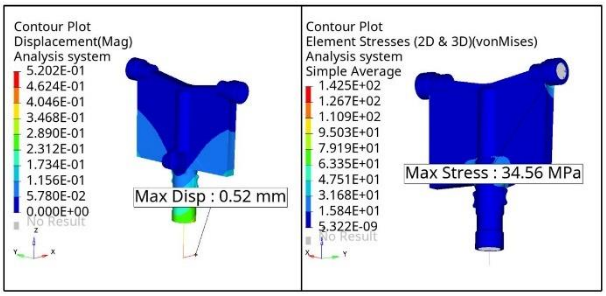

Figure 13. Drag force-displacement and stress results of bulk Trunnion

After the drag force case calculation 0.52 mm maximum displacement and 34.56 MPa maximum Von-Mises stress results are obtained.

Following the linear static stress analysis, the topology optimization problem is defined on the trunnion component. As a similar with the torque link study on previous chapter, the volume fraction and weighted compliance parameters were selected as the analysis outputs called “Responses”. The compliance values for vertical and drag subcases are 12.3 Nm and 9.1 Nm, respectively. Initially, coefficients for vertical and drag force subcases were both assigned to 1 according to the EEWC method. Then, regarding the PWC method, the coefficient of the first condition (which had the higher compliance value) was set to 1, and the coefficient of the second condition was set to 0.74, based on its ratio to the first condition. Before the run processes of the topology optimization, design, and non-design areas are defined on the bulk FEA model of the Trunnion part. These areas can be seen in Figure 14. Also, the 1-plane symmetry condition is defined on the model to get similar material distribution for both sides of the Trunnion part.

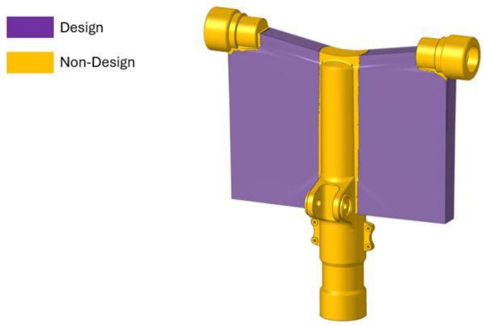

Figure 14. Design areas of Trunnion

Optimization cases for both EEWC and PWC methods are performed. Topology optimization according to the EEWC method converged at 39th iteration. The material density distribution results of the topology optimization regarding the EEWC method is shown in Figure 15. According to this material distribution, Von-Mises stresses of both vertical and drag force subcases are also calculated, and they are shown in Figure 16.

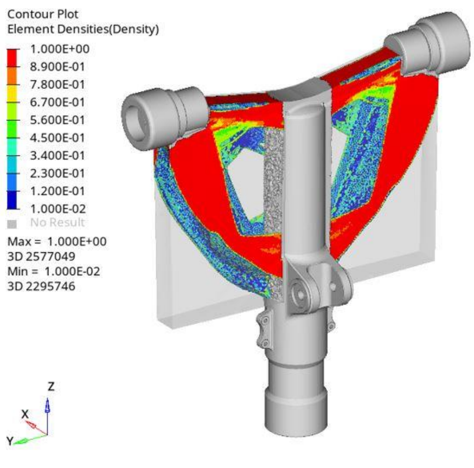

Figure 15. Trunnion material distribution according to the EEWC method

Celal Bayar University Journal of Science
Volume 21, Issue 2, 2025, p 35-46
Doi: 10.18466/cbayarfbe.1539030

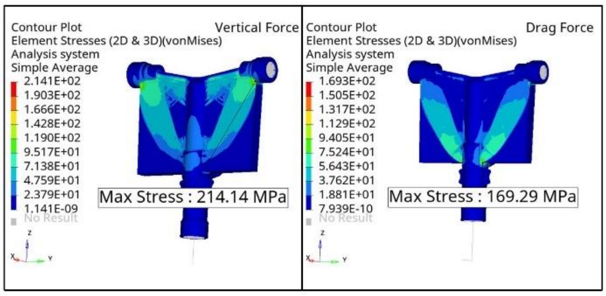

Figure 16. Optimized Trunnion Von-Mises stress results according to the EEWC method

As a result of the stress analysis, the compliance value for the first condition (vertical loading) was obtained as 28.35 Nm. The compliance value for the second condition (horizontal loading) was 21.61 Nm. Final result of the weighted compliance value to be minimized and calculated according to the formula (4) is obtained as 49.96 Nm. This value is not violating the upper constraint 50 Nm, therefore, the optimization results are feasible. Final status of the volume fraction as objective value is 0.14 and it means %86 volumetric decrease is provided.

Topology optimization according to the PWC method converged at 41^{th} iteration. The material density distribution results of the topology optimization regarding the PWC method is shown in Figure 17. According to this material distribution, Von-Mises stresses of both vertical and drag force subcases are also calculated and they are shown in Figure 18.

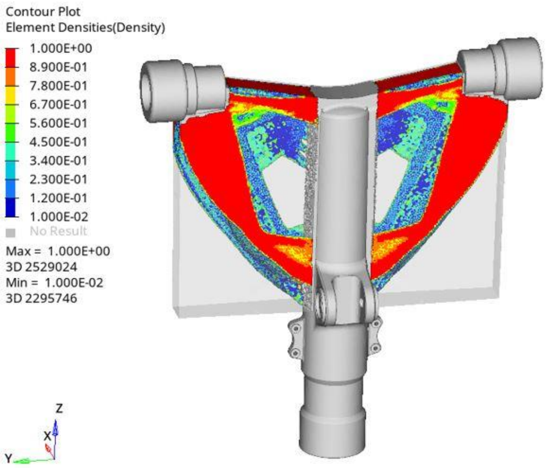

Figure 17. Trunnion material distribution according to the PWC method

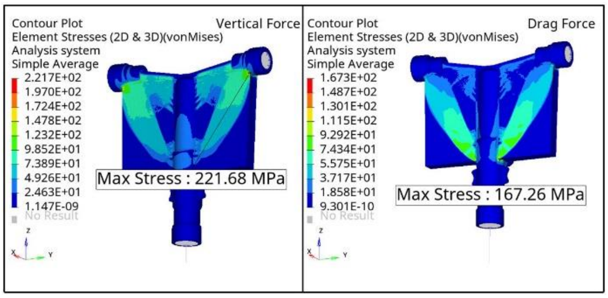

Figure 18. Optimized Trunnion Von-Mises stress results according to the PWC method

As a result of the stress analysis, the compliance value for the first condition (vertical loading) was obtained as 31.51 Nm. The compliance value for the second condition (horizontal loading) was 24.91 Nm. Final result of the weighted compliance value to be minimized and calculated according to the formula (7) is obtained as 49.96 Nm as same level with the EEWC case. This value is not violating the upper constraint 50 Nm, therefore, the optimization results are feasible. Final status of the volume fraction as objective value is 0.12 and it means %88 volumetric decrease is provided. Additionally, the stress values observed in PWC method are not much higher regarding EEWC method. Stresses in Vertical force case are 214.14 MPa for EEWC method and 221.68 MPa for PWC method therefore only 3.5% increase was observed. For drag force case the stresses for the EEWC and PWC methods are 169.29 MPa and 167.26 MPa, respectively. These values are nearly same. Therefore the stiffness of the optimized structure obtained via PWC method is not much smaller than the value obtained via the EEWC method. This status shows that in addition to effective volume reduction, similar stiffnesses with EEWC method are obtained via PWC method.

The results of the defined topology optimization for the landing gear trunnion component are shared in Table 3.

Table 3. Topology optimization results of Trunnion

Condition of Topology Optimization	Weighted Compliance [Nm]	Volume Fraction	Volumetric Decrease [%]
EEWC	49.96	0.14	86
PWC	49.96	0.12	88

4. Conclusion

In this study, topology optimization of the landing gear parts which are torque link and Trunnion were investigated. As a first study, FEA and topology optimizations of the torque link are performed. Two separate load cases called bending and torsion are used and the combined optimizations were performed. In combined studies, weighted compliance values are used as constraint functions and volume fraction values are used as objectives. There were seen that using the proportional compliance values getting from the formula (9), the PWC method is more effective than using same coefficients as 1 in weighted compliance calculation, the EEWC Method. Same comparison is applied to another landing gear part called Trunnion. The results show that the PWC method is more effective than the EEWC method since the volumetric decrease at the end of optimization iterations are higher in the PWC method. Also, the increasing on stress values for the material distribution at last iteration are not dramatical. Therefore, it can be said that the PWC method can practically be applied in industrial applications of topology optimization studies. Also, the PWC method can be used in size optimization and thickness distribution problems defined for aircraft wings and automobile chassis which facing multiple loadcases and including many sheet parts that have different thicknesses. Additionally, the total compliance output can be used in topography optimization problems. In order to constraint bead dimensions, PWC method will be an efficient method.

Findings obtained from this study also can be used very effectively in topology optimization problems considering multiple loadcases. In the aviation industry, panels and ribs located in the aircraft wing and fuselage are simultaneously subjected to bending, torsion, and shear. Helicopter rotor control and fuselage components operate under both aerodynamic loads and loads caused by the dynamic movements of the rotor. With the anticipated increasing integration of additive manufacturing in the aviation industry in the coming years, the design and production of these structures through topology optimization will become a highly significant area of research, as it enables the lightweight design of aircraft. To give an example from the automotive industry, car chassis are dynamically subjected to bending and torsion loads simultaneously during the vehicle's operation. Additionally, car bodies are designed to meet highly complex requirements simultaneously in the event of a crash, ensuring the safety of drivers, passengers, and pedestrians. Topology optimization studies with multiple loading steps defined are a crucial tool for the effective design of these structures.

Nomenclature

EEWC	Equal-Effect Weighted Compliance
FEA	Finite Element Analysis
PWC	Proportional Weighted Compliance
C	Compliance
f	Force
K	Stiffness
W	Weight factors

References

[1] N. Kaya and S. Yudar, “Hava taşıt kanallarında topoloji ve boyut optimizasyonu ile ağırlık azaltımı,” in Tusaş genç mühendisler semineri, Ankara, 2019.

[2] Raicevic et al 2023. Fatigue life prediction of topologically optimized torque link adjusted for additive manufacturing. *International Journal of Fatigue;* volume 176, 107907.

[3] G. L. Srinivas and A. Javed 2020. Topology optimization of rigid-links for industrial manipulator considering dynamic loading conditions. *Mechanism and Machine Theory;* 153: 1-16.

[4] https://www.tennesseeaircraft.net/2012/11/10/1964-182-sid-survey-part-2/ (Accessed: 05.08.2024)

[5] https://www.azom.com/article.aspx?ArticleID=9365 (Accessed: 01.08.2024)

[6] https://www.safran-group.com/products-services/boeing-fa-18-nose-landing-gear (Accessed: 05.08.2024)

[7] Infante et al 2017. Failure analysis of a nose landing gear fork. *Engineering Failure Analysis*; 82: 554-565.

[8] Freitas et al 2019. Failure analysis of the nose landing gear axle of an aircraft. *Engineering Failure Analysis*; 101: 113-120.

[9] Bagnoli et al 2007. Fatigue fracture of a main landing gear swinging lever in a civil aircraft. *Engineering Failure Analysis*; 15: 755-765.

[10] Schmidt, R. The Design of Aircraft Landing Gear; SAE International. Press: Warrendale, PA, 2021.

[11] Zhao et al 2024. Topology optimization algorithm for spatial truss based on numerical inverse hanging method. *Journal of Constructional Steel Research*; volume 219, 108764.

[12] Gu et al 2024. Nonlinear fatigue damage constrained topology optimization. *Computer Methods in Applied Mechanics and Engineering;* volume 429, 117136.

[13] Pan et al 2024. Isogeometric Topology Optimization of Multi-patch Shell Structures. *Computer-Aided Design;* volume 174, 103733.

[14] Xie et al 2024. Topology optimization for fiber-reinforced plastic (FRP) composite for frequency responses. *Computer Methods in Applied Mechanics and Engineering;* volume 428, 117114.

[15] Song et al 2024. Improving the joint quality in density-based multi-material topology optimization with minimum length scale control. *Computer Methods in Applied Mechanics and Engineering;* volume 430, 117212.

[16] Ren et al 2024. Concurrent optimization of structural topology and toolpath for additive manufacturing of continuous fiber-reinforced polymer composites. *Computer Methods in Applied Mechanics and Engineering;* volume 430, 117227.

[17] He et al 2024. Topology optimization of truss structures considering local buckling stability. *Computers & Structures;* volume 294, 107273.

[18] Yuan et al 2024. Topology optimization design for strengthening locally damaged structures: A non-gradient directed evolution method. *Computers & Structures;* volume 301, 107458.

[19] Xia et al 2024. Comparison of ground-structure and continuum based topology optimization methods for strut-and-tie model generation. *Engineering Structures;* volume 316, 118498.

[20] Feng et al 2024. Nonlinear topology optimization on thin shells using a reduced-order elastic shell model. *Thin-Walled Structures;* volume 197, 111566.

[21] Dong et al 2024. Topology-optimized lattice enhanced cementitious composites. *Materials & Design;* volume 244, 113155.

[22] Luo et al 2024. An efficient isogeometric topology optimization based on the adaptive damped geometric multigrid method. *Advances in Engineering Software;* volume 196, 103712.

[23] Saleh et al 2024. Topology optimization of vertical shear links in eccentrically braced frames. *Structures;* volume 66, 106821.

[24] https://engineeringproductdesign.com/knowledge-base/topology-optimization/ (Accessed: 12.08.2024)

[25] https://2020.help.altair.com/2020.1/hwsolvers/os/index.htm (Accessed: 23.08.2024)

[26] Zhang, W.H. and Flury,C. 1997. A modification of convex approximation methods for structural optimization. *Computers & Structures;* volume 64, pp. 89-95.

[27] Ossa E.A., Paniagua M., Handbook of Materials Failure Analysis with Case Studies from the Aerospace and Automotive Industries, Press: Butterworth-Heinemann, 2016.

[28] Gültekin, E. and Yahşi, M. 2021. A Study About Shape and Topology Optimizations on A Connecting Rod. *International Journal of Automotive Science and Technology* 5 (2): 141-146.

[29] https://www.newport.com/t/understanding-the-compliance-curve (Accessed: 22/08/2024)

[30] https://grabcad.com/library/f-16-front-landing-gear-for-rc-model-1 (Accessed: 06/08/2024)

[31] European Union Aviation Safety Agency (EASA). (2023). Certification Specifications for Large Rotorcraft (CS-29), Amendment 11. Cologne, Germany: EASA.

[32] Dong X, Jiang X, Li P, Niu T, Wang Y, Zhang J. Topology optimization structure design of shape memory alloy with multiple constraints. Journal of Intelligent Material Systems and Structures. 2024;35(10):892-906. doi:10.1177/1045389X241237581

[33] Patham KF. Redesigning Dynamic components for additive manufacturing using topology optimization. Journal of Micromanufacturing. 2024;0(0). doi:10.1177/25165984241260580

[34] Tang P, Xu W, Ding Z, Jiang M, Lv M. Research on multi-objective topology optimization of unmanned sightseeing vehicle frame based on Analytic Hierarchy Process. Advances in Mechanical Engineering. 2024;16(10). doi:10.1177/16878132241288406

[35] Ren C, Liu X, Yang X, Ma T. Crash topology optimization for front-end safety parts of battery electric vehicle using an improved equivalent static loads method. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2024;238(8):2396-2420. doi:10.1177/09544070231162137

[36] Lan K, Yu W, Huang C, Zhou Y, Li Z, Huang W. Multi-objective optimization design for anti-fatigue lightweight of dump truck carriage combined with machine learning. Advances in Mechanical Engineering. 2024;16(9). doi:10.1177/16878132241269244

[37] Yuanyao M, Dongbo L, Chunyan L, Yan W, Xiguang L, Bo W. Multi-objective optimization of traditional residential timber frames based on response surface methodology. Journal of Computational Methods in Science and Engineering. 2024;0(0). doi:10.1177/14727978241293251

[38] Wang T, Xue W, Wei M, Wu J, Luo Z, Liu R. Multi-condition and multi-objective conceptual optimization design of automotive front subframe. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2024;0(0). doi:10.1177/09544070241297046

[39] Zhu Y, Xu F, Deng X, Niu X, Zou Z. Bionic topology optimization design and multi-objective optimization of guide arm. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2024;0(0). doi:10.1177/09544070231217565

[40] Chen H, Yu P, Long J. Multi-objective optimization design of automobile seat backrest considering coupling effect. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2024;0(0). doi:10.1177/09544070241285498

[41] Najafi M, Ferreira AJM, Marques FD. Aeroelastic analysis of a lightweight topology-optimized sandwich panel. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2024;238(10):999-1017. doi:10.1177/09544100241252041

[42] Rahman M, Fricks C, Ahmed H, et al. Topology optimization and experimental validation of mass-reduced aircraft wing designs. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2024;0(0). doi:10.1177/09544100241290577