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TOPOLOGY OPTIMIZATION OF PACKAGE SEALER JAW CHASSIS OF AUTOMATIC PACKAGING MACHINE

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Abstract

After the Covid-19 epidemic, the need to reach hygienic and sealed packaged food products has gained importance and the packaging machinery sector has become an important sector. In this context, the need for special packaging machines has increased. The jaw mechanism of the packaging machine developed within the scope of the study performs the package closing function by opening and closing 200 times per minute, and the jaw chassis carrying the jaw mechanism is exposed to the same series of movements. The design of the jaw chassis should be as light as possible so that no additional load is placed on the motors that provide the movement, while its strength should be high since it carries the entire load from the jaw plates to the motors.

To solve this problem, a structural optimization solution called topology optimization, which regulates the distribution of the elements in the design volume within the framework of the determined constraints, is used. With the performed topology optimization study, it has been determined that the new solid model, which continues to provide sufficient strength when exposed to 5000 N force, provides 11% weight gain. This work has been a pioneer for new research to obtain lightweight designs.

Keywords
Topology Optimization, Packaging Machine, Jaw, Connecting Rod Mechanism, Material

1. Introduction

We need packages to protect food quality, nutritional values, taste, appearance and texture, to provide hygiene, and to meet storage, logistics, distribution, retail, information and advertising needs. In particular, food packaging processes must ensure that food packages achieve the highest possible quality for consumers.

When the size of the domestic and foreign markets of the packaging machines that make the packaging process is investigated, it is seen that it is 38.95 billion dollars on a global basis and that many foreign companies on a global basis have a large share in the market and the sector (Brody & Marsh, 1997).

Within the scope of the packaging sector, the flexible food packaging sector is growing day by day, the cost pressure is increasing, the processes must be safe, reliable and ready for automation, and the requirements related to the increase of flexibility and optimization studies are expected to meet, and the concepts of packaging-Industry 4.0 are emerging. Especially after the global Covid-19 epidemic, which affects the whole world today, the need to reach hygienic and sealed packaged food products has gained importance and the packaging machinery sector has become a very important sector for the sectors that produce all product types. *Uncovering the packaging machinery and know-how to be exported internationally has become a strategic priority.* When the general structures of packaging machines are examined, it is seen that the chassis and packaging flow process are in horizontal, vertical and similar axes, and the types of packaging machines are named according to this axial orientation (for example, mattress packaging machine). In addition, the manufacturability of package types can be adjusted horizontally and vertically, etc. by the machines. It is also related to the case of being in machine types.

The packaging machine that will be included in the scope of the study is used to produce packs that can form the small package type and to bring the "form, fill and seal" function in general and to pack particles or multiple objects. At the beginning of the packaging operation, the package film is pulled over a forming collar (mold, forming collar, shoulder), and then after all necessary processes (pack forming, package edge cutting and sealing, product filling, package mouth (top) sealing, package transfer, classification) and cartoning) a fully sealed protective package full of product is created. While all the relevant operational stages are very important, the milestones of the packaging process are the development of package sealing systems (Merabtene, et. al. 2021).

When the most important criteria regarding the packaging processes in the packaging industry are examined, it is seen that there are criteria such as the number of packages per unit time (hence the jaw welding/sealing speed), the package sealing (indirectly the package welding/sealing quality) and the area occupied by the packaging machine. Traditional vertical packaging machines contain a single-sealing jaw intermittently and can perform packaging operations at low capacity and quality due to this mechanical limitation. In the state of the art, more than one packaging machine investment is made to increase the packaging capacity in a food factory and to obtain more packaged products per unit of time. In particular, improved sealing jaw systems, etc., of capacity increase. It has been seen that it can be done with systems to a very limited extent and it has been determined that two separate machines must be purchased to double the capacity. In this case, the cost of purchasing more than one machine (purchasing, maintenance, spare parts, control operator costs, etc.) is incurred and more packaging line space has to be allocated.

The motto of "double capacity in one machine" has been revealed as a result of the idea of creating a product with the capacity of two machines with a single machine cost by occupying the less lateral area. To bring this idea to life, a special sealing jaw with double capacity was designed instead of the traditional package sealing jaw (Messenger, 1999). The demand for the special jaw to perform package sealing operations with the increase in capacity has revealed the need for this system to have a rigid, light, and optimized motion system and to include a jaw frame component. In this study, the design process of this component, which consists of aluminum material, by the demand for the special jaw to perform package sealing operations with the increase in capacity has revealed the need for this system to have a rigid, light and optimized motion system and to include a jaw frame component. The operating conditions of the system are explained to reduce the weight of the package adhesive jaw chassis of the packaging machine.

Topology optimization was applied to create the lightest jaw chassis design suitable for system operating conditions. Structural analysis verification of the optimized model was also done with the help of the Solidworks Simulation program with the Finite Element Analysis method.

2. Literature Review

In all sectors where mechanical and mechatronic components are involved, these components are demanded to be more durable but lighter. Since less use of the materials that make up the component means the production of the component at less cost, the development of lighter parts also becomes an important cost target. This situation requires applying some optimization methods such as topology optimization to make better designs.

Topology optimization, all details of which will be explained in the next sections, is used in various applications, especially in the automotive industry. As an example of automotive industry applications, the weight of the brake pedal of the Formula SAE vehicle has been achieved with a topology optimization design without reducing the strength (Albak, 2019).

When we look at the machinery sector, we encounter a different study that includes the detailed design of the clamp cylinder for a 1000-ton injection molding machine with topology optimization. In the aforementioned study, modeling and FEA are done for the newly designed 1000T clamp cylinder and validated by theoretical calculation and acceptance criteria. The optimized model is equally powerful and light compared to the current model (Niral & Chauhan, 2013).

According to the literature research we have done, one of the most interesting studies on topology optimization has been done in the biomedical field. In recent years, the disease called degenerative spinal instability has been seen frequently. The cause of this disease is the deterioration of spinal stability and instability over time due to spinal degeneration. This disease is effectively treated with a special biomechanical cage. In the related article, the biomechanical function of the lattice was evaluated using topology optimization and finite element method (FEM). Thanks to the lower volume design, the increased space allows more bone grafts to be placed and the cage saves material. (Zhong, et. al. 2006).

3. Methodology

Numerous structural design alternatives are needed to create design configurations that meet various performance indicators such as strength, weight and cost. Therefore, in the design phase, structural optimization methods are important to create designs with the lowest mass but maximum strength performance according to the determined boundary conditions (Lee, et. al. 2012).

According to the types of design variables to define the designed geometry, these methods are classified as size, shape or topology optimization methods. The objective function and constraints should be expressed as functions that can be defined in terms of design variables. Structural optimization techniques change the size, shape and topology of the design depending on the boundary conditions and constraints to which the design is subject until the structure is optimal.

Two different methods, the homogenization method and the density method, are used in topology optimization to determine the distribution of elements. The most general method used to solve this problem is to use continuous variables ranging from 0 to 1 instead of the integer variables determined for the volumetric density value x_i and to introduce some limitations (penalization) to direct the results to the values 0 and 1. After this process, the optimization problem in a given design space evolves into a dimensioning problem expressed as a function of the strength matrix and material density. This material model used to perform the topology optimization is called SIMP (Solid Isotropic Material with Penalization) (Zheng, 2007).

Here $\breve{K}$ is the penalized stiffness matrix of the element, 'K' is the real stiffness matrix of the element, 'ρ' is the density and 'p' is the penalty coefficient and it always takes the values K>1

$$\breve{K}(\rho) = \rho^p K \quad (1)$$

"The smallest empty element represents the p_{min} value. The reason why this value should be different from 0 can be understood from the calculation of the stiffness matrix according to the SIMP method given in Equation 2. The modulus of elasticity also varies, as the material density varies between elements. The modulus of elasticity for each element is calculated as in Equation 3. As it can be understood from the equation, the penalty factor p forces each element to be an empty or solid element, reducing the effect of elements with intermediate density. Different equations are used according to the set goal and constraints. The SIMP method algorithm tries to reach the given goal through an iterative process. These iterations continue until the changes in the target functions satisfy the desired convergence criteria. (Zhang, et. al. 2020).

$$K = \sum_{e=1}^{N} [\rho_{min} + (1 - \rho_{min})\rho_e^p] K_e \quad (2)$$

$$E = E_0 \cdot \rho^p \quad (3)$$

The penalty factor p reduces the contribution of elements with intermediate densities (gray elements) to the overall stiffness. The penalty factor drives the optimization solution to elements that are solid black (p_e= 1) or invalid white (p_e = p_{min}).

Numerical experiments show that a penalty factor value of p = 3 is appropriate. The decrease in the material modulus of elasticity of the element causes a decrease in the stiffness of the element. Figure 1 shows the SIMP method interpolation scheme (Ozarpa, et. al. 2021).

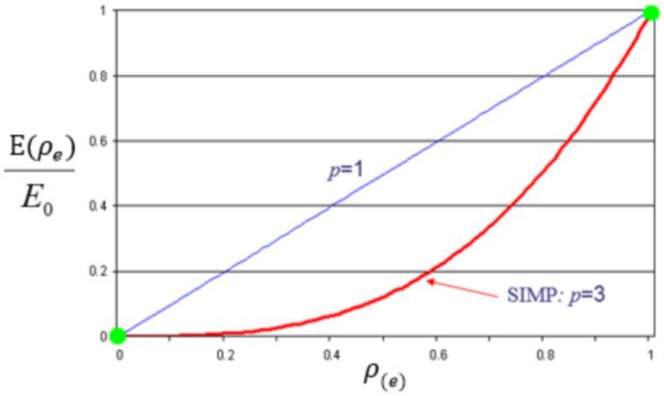

Figure 1: *SIMP İnterpolation Scheme*
(Source: Ozarpa, et. al. 2021)

In summary, the topology optimization problem is formulated as the maximization of stiffness depending on a mass constraint. Topology optimization is used in various applications in the automotive industry.

For example; used topology optimization to improve the structural performance of a rear suspension subframe (Yildiz, et. al. 2004). *Within the scope of the study, this structural optimization method will be used in a special chassis.*

4. Package Sealing System

The machines called packaging machines or packaging sealing systems are systems that can pack in a series without the need for manpower. Package sealing is achieved by contacting the front and rear thermal conductive plates of the special jaw and welding the thermoplastic film material between the two jaws by melting. The opening and closing movement of these jaw plates to each other is provided by a connecting rod mechanism. The connecting rod mechanism shaft carries out the up and down movement of the chassis, which carries the jaw drive motors, jaws and similar components, with the driving power it receives from the engine that provides rotational movement. Figure 2 shows the package sealing mechatronic system components with which the chassis in the study interacts.

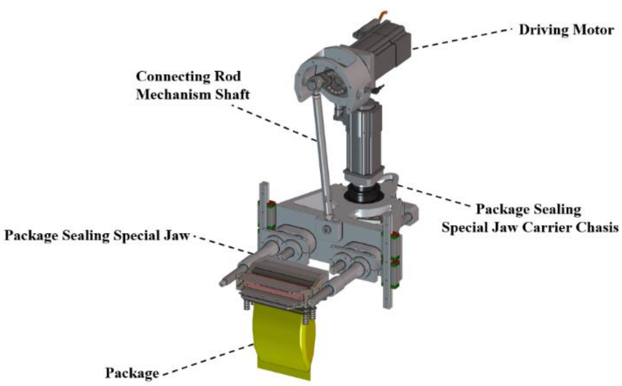

Figure 2: *Illustration Of Packaging Machine Package Sealing Mechatronic System Components (Source: Self/Authors' Own Illustration)*

5. Topological Optimization of Pack Sealer Jaw Chassis

Contrary to traditional packaging systems, product-filled packages with increased capacity can be produced with the special jaw system, which will be examined in terms of operation. The related new system should realize much more than the amount of packaged product that two traditional vertical packaging machines will produce on a unit time basis, with specially placed components in a single machine and with a unique design by occupying much less space.

Thus, within the scope of the study, impermeable, durable and hygienic packages with a package film structure that flows easily on the system without wrinkling and deformation will be obtained with rapidly lightened, durable and rigid mechatronic component designs.

At this point, the design of the chassis that carries the jaw components, which serve as package sealing, is very important. Since it will carry the drive motors, jaw structures, resistances, jaw shafts and all similar components on the relevant carrier chassis, it must meet the strength conditions. However, the lower the weight of the chassis, the less load will be placed on the motors that move in the +-Y axis direction during the sealing process, and it will be possible to select motors with lower capacity and lower cost. The relevant chassis must be designed to withstand a force of 5000 N.

Topology optimization has been used to design the lightest package sealer jaw chassis that meets the required strength requirements. Solidworks Simulation program special modules are used for topology optimization and related finite element modeling. Analyzes were performed in a single step and results for static analysis are listed.

In addition, the topological optimization of the model was carried out with 50% mass reduction and the best stiffness and weight ratio condition. To represent the motor and similar loads carried by the relevant chassis, a force of 5000 N was applied to the entire surface in the '-Y' direction and the part chassis table was fixed on the left and right flange surfaces. Figure 3 shows the initial design volume, unloading zones and nodes.

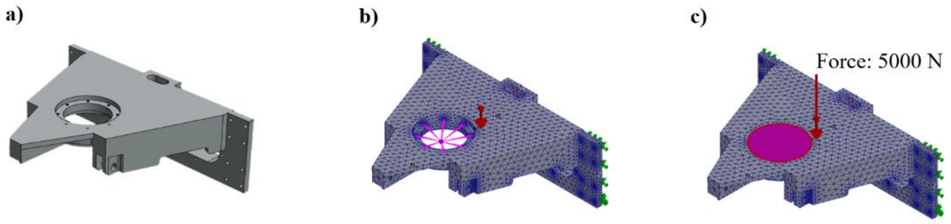

Figure 3: *Determination Of Topology Optimization Boundary Conditions, A) The First Design Showing The Design Volume, B) Unloading Desired And Undesired Areas, C) Boundary Conditions For Jaw Frame Structural Analysis*
(Source: Self/Authors' Own Illustration)

In the topology optimization study of the package sealing jaw carrier chassis component, the areas where unloading is desired as the design variable, the stress value of 195.00 MPa, which is determined to be safely less at the yield stress of the 5000 series aluminum alloy, as the constraint, and the optimization purpose is determined as weight reduction.

Aluminum material parameters to be used as constraints in topology optimization are given in Table 1. To take into account the manufacturability of the model to be optimized, when performing topology optimizations, since the part is symmetrical to the XY plane, the fact that it is symmetrical to this plane has been added as a manufacturing constraint.

Table 1: *Mechanical Properties of 5000 Series Aluminum Alloy*
(Source: Self/Authors' Own Illustration)

Elastic Modulus (GPa)	Poison Ration	Yield Strength (MPa)
70	0.33	195

6. Results and Discussion

Static analysis and topological optimization were performed for the full (not emptied) state of the package sealer jaw chassis component coded in the system as AY-00172935. The analysis results made according to the operating conditions required by the system, the place where the force is applied and the reference value taken, were compared with the static tension value of this part in the packaging machine system and the yield strength value for the part material.

As a result of the static analysis performed to observe the deformation of this part, it was determined that the maximum stress value of 23.575 MPa was lower than the yield strength of 195 MPa. *In this case, this part has been observed to be safe.* In addition, thanks to the topology optimization, a revised design of the model was made by applying a mass reduction with a similar strength value. The element density distributions according to the topology optimization results are shown in Figure 4.

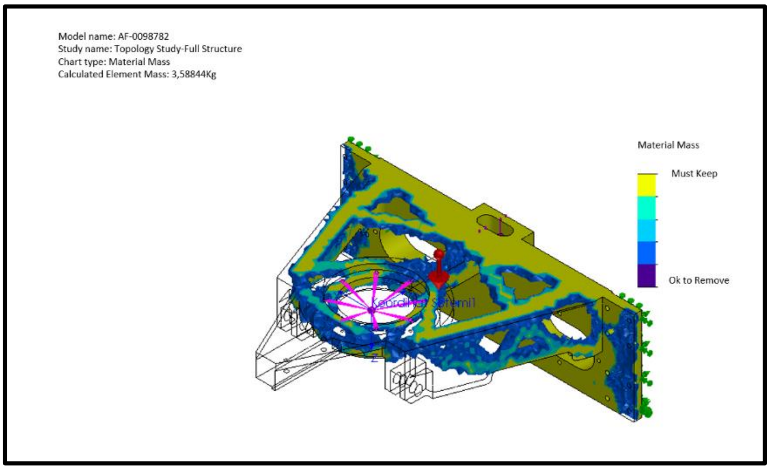

Figure 4: *Topology Optimization Result*
(Source: Self/Authors' Own Illustration)

The areas shown in yellow show the areas that should not be emptied (Must Keep), while the areas in blue color and close tones show the areas that should be emptied (Ok to Remove). An iterative approach was used to reach this design image with general lines. Based on the topology optimization element density distribution map, the design lines were determined for the chassis and the new model is shown in comparison with the initial model in Figure 5. This new model has slots in the form of triangular geometry, especially in the chassis end areas and trapezoidal geometry slots in the chassis upper surface areas. Although the weight of this part is theoretically reduced to 3.59 KG, according to the approximately 50% mass reduction condition, it will be higher in the final model due to stiffness and similar static structure limitations.

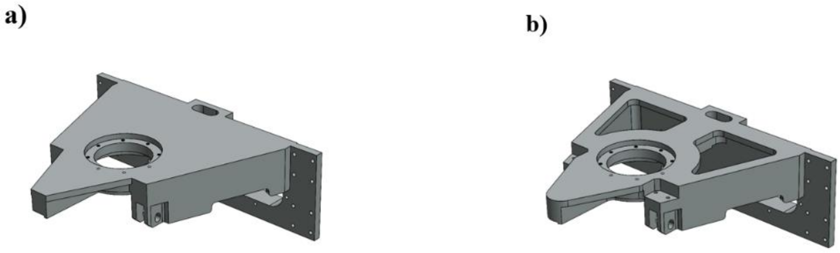

Figure 5: *Design Model Comparison Before And After Topology Optimization A) İnitial Model B) New Model*
(Source: Self/Authors' Own Illustration)

For the revised model, static analysis was performed again to observe the deformation of this part. As a result of this analysis, it was determined that the calculated maximum stress value of 24.550 MPa was lower than the yield strength of 195 MPa. In this case, it has been observed that the new model, which has a new form with topology optimization, is safe.

In Figure 6, the results of the comparative structural analysis of the old and new models are compared with the stress results and displacement results. Considering the displacement results, it was determined that there was no significant difference between the old and new models.

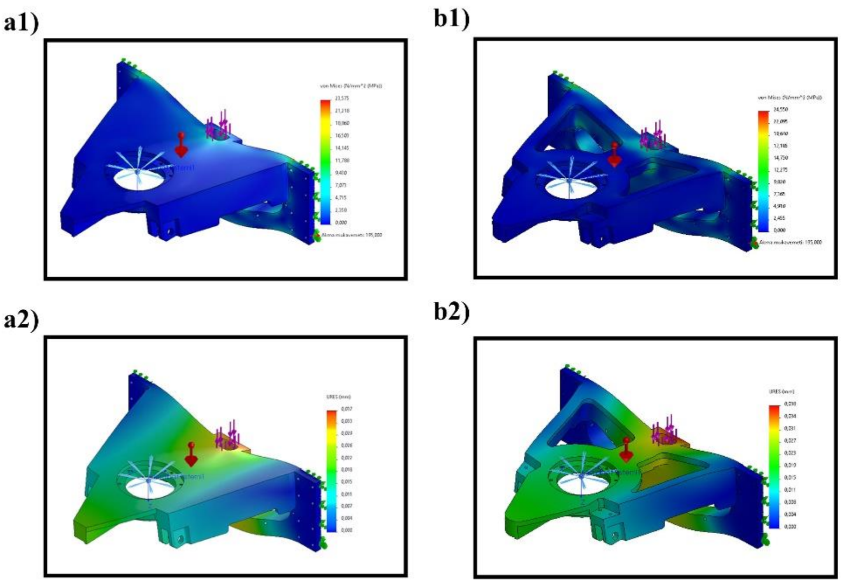

Figure 6: *Comparative Structural Analysis Results Depicted By Color Scale A1) Initial Model Stress Result, A2) Initial Model Displacement Result, B1) New Model Stress Result, B2) Result Of New Model Displacement*
(Source: Self/Authors' Own Illustration)

Table 2 presents the numerical results of the comparative structural analysis of the initial and new models. According to the results of the structural analysis, there was no significant loss of strength in the new model of the package sealing jaw chassis, in which certain parts were unloaded with topology optimization, and the weight of the initial model was reduced to 6.16 KG in the new model, which was 6.86 KG.

Table 2: *Comparative Structural Analysis Numerical Results*
(Source: Self/Authors' Own Illustration)

Initial model Maksimum Stress (MPa)	New model Maksimum Stress (MPa)
23.575	24.550
Initial model Maksimum Displacement (mm)	New model Maksimum Displacement (mm)
0,037	0,038

Static structural analyzes for the new and old models are not sufficient alone for the design verification phase. It is also necessary to examine the effect of this weight reduction in the chassis component on the connecting rod mechanism shaft, which moves the chassis in the +-Y axis direction with the components on it and is connected to the chassis component. Since this shaft is subject to an iterative movement depending on time, it is necessary to establish a dynamic analysis model and to perform analysis according to this model. As can be seen in Figure 7, as a result of this dynamic analysis, no stress value exceeding the limit value was observed for the shaft component under dynamic load. *Thus, it has been shown that the weight of the new lightweight chassis model does not cause an undesirable effect on the connecting rod shaft.*

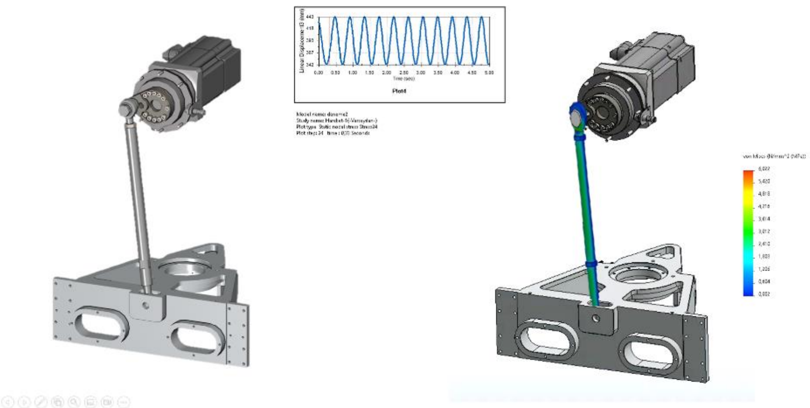

Figure 7: *Connecting Rod Shaft Dynamic Analysis Study A) Real Model Display, B) Dynamic Analysis Display*
(Source: Self/Authors' Own Illustration)

7. Conclusion

After Covid-19, the need to develop high-capacity packaging machines has emerged to meet the growing demand for hygienic and packaged food products to reach quickly. As a result of the idea of creating a twin system, which will be a very important alternative to this need, a double-capacity sealing jaw packaging system has been developed. With the new special jaw structure, it is aimed to stitch 2 times more packages with the thermal sealing system and to produce 50 packages x 2 = 100 packages per minute. This situation reveals that the special connecting rod drive system must make 100 cycles per minute.

In other words, the jaw chassis, which is connected to the connecting rod mechanism by means of a shaft, must move 50 times down and 50 times per minute with the loads on it. This very fast movement should not deform the jaw chassis due to stress under dynamic conditions. At the same time, it should be aimed that the chassis weight is designed to be minimum so that it does not impose an additional load on the drive motors, which are already exposed to dynamic load. *In this study, topology optimization, which regulates the distribution of the elements in the design volume within the determined constraints, is used to increase the strength while reducing the weight.*

Topology optimization includes different methods such as density-based method, evolutionary structural optimization, and so on. As mentioned briefly in the relevant parts of the study, many computer programs that can be optimized for topology use the SIMP method, which is derived from the density-based method. The Solidworks program we use within the scope of the study also progresses on this method. In the new system related to the work carried out using this program, the double-capacity jaw chassis design has been optimized topologically and has a geometric form with a special triangular and hollow structure. With the topology optimization, an 11% lighter chassis was obtained compared to the first design. The tensile strengths of the shaft and its connecting elements have been maximized with the lightweight chassis, the engine selected in appropriate dimensions and the simulated connecting rod dynamic system, and this has been confirmed by the finite element analyses made. It should be noted that the topology optimization method also has some limitations. To obtain a lighter part, hollow forms created on the design may increase the production cost of the part or make it impossible to manufacture the part with current production techniques.

In addition, hollow forms created by ignoring the plane of symmetry of the piece may incorrectly change the center of gravity of the piece. In this context, while applying the topology optimization method, model constraints such as manufacturability, symmetry, etc. Adding the criteria is very important to obtain more feasible results.

In future studies, the different components of serial machines such as packaging machines can be examined with topology optimization and the manufacturability of the parts can be increased by integrating the manufacturing constraints into the process in more detail.

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