

Article

Study on Sustainable Lightweight Design of Airport Waiting Chair Frame Structure Based on ANSYS Workbench

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Abstract: The airport waiting chair frames, as an important part of the overall seating, must be designed to provide comfort, safety, and aesthetic appeal. While the airport furniture industry has made progress in terms of sustainability, more efforts are needed to improve material selection, manufacturing processes, and supply chain management to support the development of sustainable furniture. This study proposes innovative ideas for the lightweight design of the frame, based on the limitations of the existing design. Firstly, structural innovations are discussed, non-traditional mesh panels and curved rounded designs are discussed, and non-introduced mesh panels and curved designs are used to enhance the strength and stability of airport waiting chairs and enhance their overall performance. Secondly, innovations in lightweighting have focused on adjusting the thickness dimensions to enhance comfort, material utilization, and sustainability as well as to achieve a lightweight and thin appearance effect. In order to determine the optimal ranges of values for the thickness of the seat surface support strip (P5), the thickness of the backrest strip (P3), and the thickness of the seat panel (P1), nine groups of chairs with different frame sizes were tested using an orthogonal experimental method. Based on the experimental results for size and topology optimization, NX2312 software modeling will be imported into ANSYS Workbench for static analysis. Using the optimized results, the use of 2.842 kg of steel was successfully reduced by 34.8% to ensure the seat's stability. This provides a reference and idea for the digital and standardized innovative design of airport waiting chair furniture structure in the future. Through digital design and lightweight optimization, material savings and effective use of resources can be achieved, promoting the goal of sustainable development.

Keywords: airport waiting chairs; sustainable design; finite element; lightweighting; topology optimization



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1. Introduction

An airport waiting chair's frame, a crucial component of the seat, is subjected to high-frequency movements when in use. By strengthening our understanding of the force analysis and structural condition of the frame and improving its design, we can increase the seat's durability and sustainability [1]. First off, a lack of thorough research on frame design has resulted in problems like damage, distortion, and breaking of seats during usage, particularly in the areas of seat panels and backrest strips, as designers mostly rely on the experience and imitation of workers. Secondly, there is also a situation where the inner frame of the airport waiting chairs is not tightly adhered to the outer polyurethane foam material, which leads to the seat surface becoming loose and falling off, thereby increasing resource waste and environmental impact [2–5]. Finally, due to the smaller curvature of the seat corners for visual aesthetics, passengers have a higher probability of colliding when passing by, thereby reducing their overall satisfaction with the airport. This article conducts

in-depth analysis and optimization of the frame structure to enable it to withstand high-frequency movements and major loads such as pressure and impact, thereby improving the stability and safety of the seat [6–8]. Since the frame is the fundamental component of the chair, the usual conservative calculation method may cause the chair's stability to receive too much attention.

Simultaneously, by conducting more thorough testing and rework during the design phase, problems can be found and solved early on, minimizing damage and seat obsolescence, extending the seat's useful life, lowering resource consumption and environmental impact, and achieving sustainable development. Using recyclable and renewable materials to make the frames of airport waiting chairs can further improve their sustainability by facilitating recycling and lowering waste production.

The need for longevity grows together with the expansion of airport waiting chair production [9]. Since the frame is the fundamental component of the chair, the usual conservative calculation method may cause the chair's stability to receive too much attention.

This ultimately causes the steel's thickness to continuously thicken, wasting a significant number of resources in addition to increasing the amount of material utilized [10–13]. This issue is resolved by using a lightweight design, which lowers the bulk of the entire frame by logically altering the proportions of important parts like foot braces, support strips, and seat panels. The optimum design has two basic goals. The first is to examine how the stability and safety of the frame structure are affected by the varying sizes of essential components. The second is to achieve a lightweight design by lowering the total frame mass [14–17]. This paper uses structural steel as the basic material. Steel is punched, chopped, and pressed into the appropriate sections, which are then welded into a complete frame [18].

In addition to lowering material usage, this lightweight design also lowers the seat's weight, increases transportation effectiveness, lowers energy consumption and carbon emissions, and complies with sustainable development standards.

In this paper, structural steel is used as the base material, and the parts are processed and welded into a whole frame by pressing steel, cutting, and punching [18]. Many scholars have also conducted research in this area; Ziming Tang et al. proposed a new type of seat bracket structure based on the lightweight requirements of electric bus components and the performance advantages of hot-rolled ultra-high-strength steel [19–21]. By altering the material, the entire vehicle can be made lighter. Zhang Lei used the cross-section size of the extension arm as an optimized design variable, and the final weight reduction rate could reach 15.2%. Li Kun optimized the value of key design dimensions to achieve the lightweight design of the frame while meeting the strength of the host frame. Firstly, by controlling the size of the key parts of the frame, the mass of the overall frame can be appropriately reduced. Secondly, by optimizing the design variables, a 3D model is built using NX2312 and imported into ANSYS Workbench 2022R1 simulation software, which will provide more accurate, fast, and visualized mechanical analysis results. For the shape analysis of the airport waiting chair frame, "size optimization" and "topology optimization" are selected to improve the structure successively. Using this innovative method in the article, the best design scheme is determined under the premise of satisfying the stress value and deformation amount [22].

The goal of lightweight can be achieved by reducing the overall mass of the frame, this will improve the product in the market, lower production costs, shorten the time needed for product development, reduce energy consumption and carbon emission, and lessen resource consumption and the environment impact, all of which will contribute to the product's increased sustainability [23–27].

2. Materials and Methods

The seat plate, lateral support strip, two sides of the shaping strip, and foot support make up the general structure of the airport waiting chair. However, in the traditional furniture structure design, theoretical calculations or empirical value method is the main

method; this makes the design analysis method difficult to understand and operate and will result in resource waste. Moreover, unreasonable size will increase production costs, will affect production efficiency, and cannot ensure product quality [28]. Thus, the precise procedure for creating a digital design process based on conventional approaches is depicted in Figure 1.

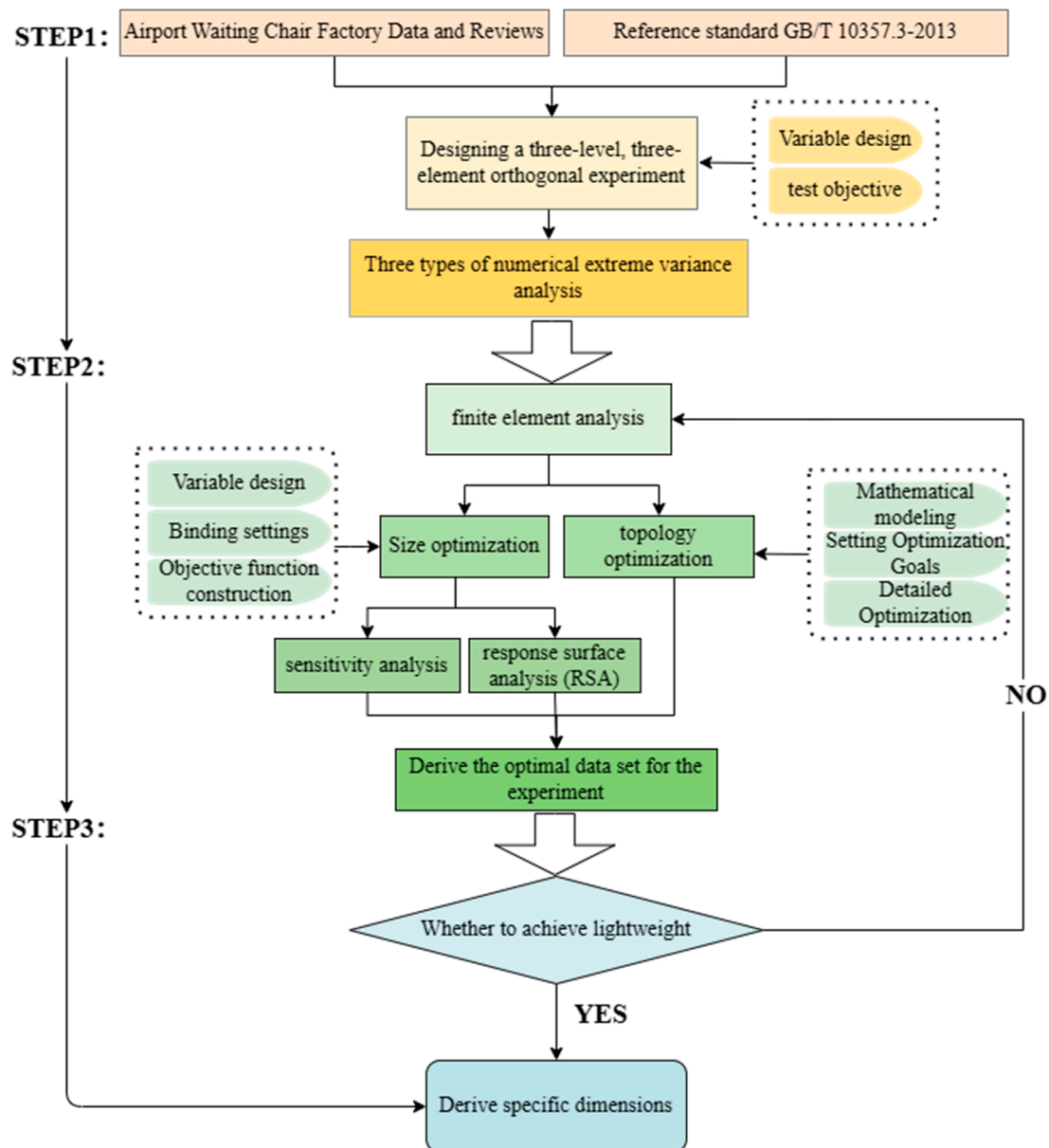


Figure 1. Design flow chart [29].

The force loading point location was determined using the seat surface backrest joint durability testing machine for mechanical testing by GB/10357.3-89 standards [30]. Since there is no standard for testing the seat frame separately, the seat is tested as a whole.

This paper presents the design of three elements of three-level orthogonal experiments. Specifically, the design of nine chairs with different size parameters for mechanical properties testing is presented. These chairs were created primarily by varying the seat surface support strip thickness, backrest strip thickness, and seat panel thickness of three parts of three different sizes. The current market's airport waiting chair's frame sizes are compiled and arranged, and finally, the overall frame size is controlled within 420 mm × 504 mm

× 600 mm (±5). The force loading point location was determined using the seat surface backrest joint durability testing with GB/10357.3-89 standards [30].

The frame will be processed into a complete seat for the experiment because there isn't a precise standard to define the mechanical qualities of the frame test. Structural steel is employed as the primary raw material for the entire frame and is more commonly used in furniture frames due to its high strength, plasticity, durability, construction convenience, and sustainability [31–34]. The material properties of structural steel are shown in Table 1.

Table 1. Material properties of structural steel.

Name of Material	Material Density (kg/m ³)	Tensile Yield Strength (MPa)	Young's Modulus (GPa)	Poisson's Ratio
Structural steel	7850	250	200	0.3

It is feasible to identify the suitable range of design parameters, where the maximum static load on the surface of the seat is the weight of the human body during normal use by analyzing and assessing the static loads of airport waiting chairs during normal use. In this investigation, the maximum human weight load ought to be chosen. According to the standard GB/10000-88 [35] "Chinese Adult Body Type", 95% of Chinese adult males aged 26–35 years old weighed 74 kg, adult females weighed 65 kg, adult males aged 36–60 years old weighed 78 kg, and adult females aged 36–55 years old weighed 70 kg, therefore a load of at least 780 N should be applied.

However, there is inadvertent use due to the location of the airport waiting chairs being in a high-frequency use area; therefore, for the fourth level of requirements, utilize the GB/T 10357.3-2013 standard [29]. After comprehensive consideration, a load of 550 N was added to the backrest and 1600 N to the seat surface in the experiment. The overall displacement (i.e., the average of the movement distance of the four support legs of the seat), the peak force of the backrest (i.e., the maximum impact force applied to the backrest at the moment of contact with the machine), and the peak force of the seat surface (i.e., the maximum impact force applied to the seat surface at the moment of contact with the machine) were measured to evaluate the overall influence of the three factors, and then to obtain the ideal range of values of each size parameter. Secondly, the technique for optimizing the frame is inferred from the correlation between various factors. Finally, the parameter optimization approach was utilized to perform calculations, data analysis, and comparisons based on the fundamental instances of airport waiting chair frames that were gathered to identify the optimal coverage of dimensions [36]. A process of assessment and optimization like this can improve the performance and quality of the seat while cutting down on superfluous design waste and adhering to sustainable development standards.

Finite element analysis techniques are progressively being used in the field of furniture structure design as a result of the ongoing development of finite element software functionalities. It is primarily used for optimization analysis of local brittle point or drop test, impact load, overall or local static load, and furniture or its components. It is a popular and efficient simulation technique that can analyze the stresses and strains of a complex frame structure and guarantee that the sizes and shapes of the furniture components satisfy all functional, esthetic, and strength requirements. Mesh generation and other operations on the constructed model are carried out in this study using ANSYS Workbench 2022 R1 finite element software [37]. Next, the recommended range of values in the earlier finite element analysis techniques are progressively being used in the field of furniture structure design as a result of the ongoing development of finite element software functionalities.

It is mainly used for furniture or its components for overall or local static load, impact load, drop test, and local brittle point optimization analysis. It is a popular and efficient simulation technique that can analyze the stresses and strains of a complex frame structure and guarantee that the sizes and shapes of the furniture components satisfy all functional, esthetic, and strength requirements. Mesh generation and other operations

on the constructed model are carried out in this study using ANSYS Workbench 2022 R1 finite element software [37]. In order to finally arrive at a set of optimal dimensional data, the ideal range of values from the previous section is optimized for dimensioning and topology optimization. The maximum deformation and maximum equivalent stresses are then controlled within a reasonable range based on sensitivity and response surface analysis [38].

3. Mechanical Testing and Analysis

For the accuracy of the test, the frame was combined with other materials of the seat to form an entire airport waiting chair for the test, in order to explore the effects of changes in seat frame dimensions on seat structure. In the design process, it is necessary to consider these effects comprehensively and make reasonable size adjustments to meet the requirements of the structure. The airport waiting chair frame external dimensions control in 420 mm × 504 mm × 600 mm (± 5) was produced, of which the main part of the seat surface support is the strip thickness; the thickness of the backrest strip thickness is designed for 3 mm, 4 mm, 5 mm three steps, and the thickness of the seat panel is designed for 2 mm, 2.5 mm, 3 mm three steps. The set size can cover common thicknesses and reflect the impact of thickness differences on the results. The most important thing is that it is very representative in practical applications and widely used in the production of specific frameworks, better reflecting the needs of actual production and application.

The following is the loading load for the overall seat: (1) for the load of the seat surface, the seat is supported by the ground, its y-axis movement is restricted, and the load is 1600 N. The loading point is at the centerline of the seat, which is 100 mm from the front edge of the sea and is loaded 10 times. (2) For loads on the seat backrest, with a load of 550 N, the front leg's movement is restricted in all directions, and the rear leg's translational freedom is restricted in the y-axis direction. All of the side leg freedom of the chair is then restricted after the translational freedom of the leg's lateral load o is restricted in the y-axis and equilibrium load of 1600 N is applied on the seat surface and loaded 10 times.

This experiment mainly investigates the effects of the seat surface support strip (P1), the backrest strip (P3), and the dimensions of the seat panel (P5) on the overall displacement, the peak backrest force (average value), and the peak seat surface force (average value). The orthogonal test factor levels are shown in Table 2. Specific test results are shown in Table 3.

Table 2. Orthogonal test factor levels.

Level	Considerations		
	P1 Seat Support Strip Thickness (mm)	P3 Backrest Strip Thickness (mm)	P5 Seat Panel Thickness (mm)
1	3	3	2
2	4	4	2.5
3	5	5	3

Table 3. Orthogonal test program design and test data.

	Thickness Level			Overall Displacement (mm)	Maximum Value of Backrest Force (N)	The Maximum Value of the Seat Force (N)
	P1 Seat Support Strip Thickness (mm)	P3 Backrest Strip Thickness (mm)	P5 Seat Panel Thickness (mm)			
1	1	1	1	2	460.3	1135.8
2	1	2	3	1.68	471.9	1166.8
3	1	3	2	1.72	464.6	1146.9
4	2	1	3	1.65	481.4	1195.8
5	2	2	2	1.66	476.1	1189.4
6	2	3	1	1.42	486.7	1191.6
7	3	1	3	1.35	498.7	1220.5
8	3	2	1	1.41	492.5	1217.4
9	3	3	2	1.32	502.4	1225.3

Based on the measurements, it was discovered that while the peak backrest force and the peak seat surface force showed an overall growing trend, the total displacement showed an overall decreasing tendency as the three elements' sizes increased. This suggests that adjusting the size of the frame of an airport waiting chair can significantly affect the overall stability and longevity of the seat. The JMP data analysis program was developed to statistically evaluate the experimental data, which are shown in Figure 2, in order to investigate the proper size range of each component.

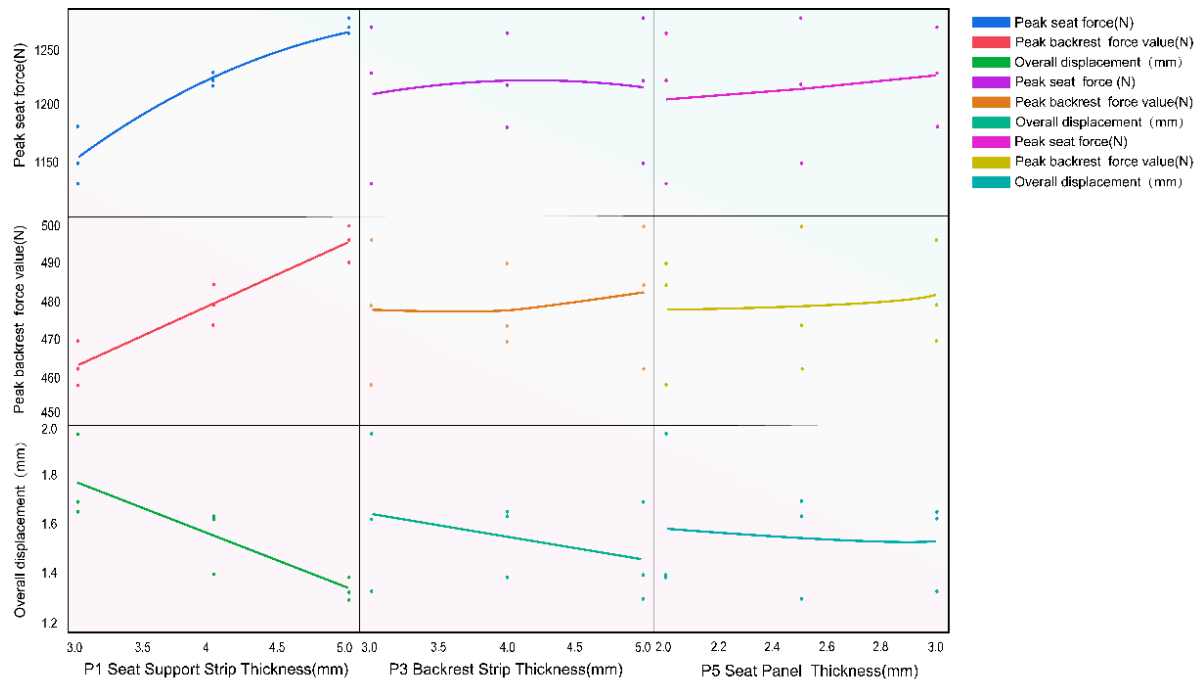


Figure 2. Three-factor, three-level JMP analysis diagram.

Based on the measurements, it was discovered that while the peak backrest force and the peak seat surface force showed an overall increasing trend, the total displacement showed an overall decreasing tendency as the three elements' sizes increased. This suggests that adjusting the size of the frame of an airport waiting chair can significantly affect the overall stability and longevity of the seat. The JMP 17 data analysis software was introduced to statistically analyze the experimental data, which can be seen in Figure 2, in order to investigate the proper size range of each component.

3.1. Polarization Analysis

The results will be analyzed through an orthogonal experimental design with polar deviation, which will be used to assess the degree of influence of the three factors on the variable; when the polar deviation is larger, it means that the change in the level of the factor has a greater impact on the indicator, i.e., the factor is more important [39–41].

3.1.1. Overall Displacement Polarization Analysis

Overall displacement of the range calculation results is shown in Table 4; the seat surface support strip, backrest strip, and seat panel of the extreme difference were 0.44, 0.18, 0.05, which can be obtained on the overall displacement of the influence of the factors arranged from large to small, $P1 > P3 > P5$, and then compared with the same factor at different levels of the average value "k", can be obtained at different levels of the indicators of the size of the impact. Observing the trends in Figure 1, it is concluded that the most important factor for the overall displacement is P1; and the optimal ranges for the three factors are 4–5 mm for P1, 4–5 mm for P3, and 2.4–2.8 mm for P5.

Table 4. Calculation results of overall displacement polarity.

Items	Level	P1 Seat Support Strip Thickness (mm)	P3 Backrest Strip Thickness (mm)	P5 Seat Panel Thickness (mm)
K-value	1	5.4	5	4.83
	2	4.73	4.75	4.7
	3	4.08	4.46	4.68
K _{avg} value	1	1.8	1.67	1.61
	2	1.58	1.58	1.57
	3	1.36	1.49	1.56
Best level		1	1	1
R		0.44	0.18	0.05

3.1.2. Analysis of Peak Polar Deviation of Backrest Force Values

Backrest force peak range calculation results are shown in Table 5, the seat surface support strip, backrest strip, and seat panel of the extreme difference were 32.3, 4.5, and 4.9, which can be obtained on the overall displacement of the influence of the factors arranged from large to small: P1 > P5 > P3. Compared with the same factor at different levels of the mean value “k”, this can be obtained at different levels of the indicators of the size of the impact. By looking at the trends Figure 1, the following conclusions are drawn: for the peak backrest force, the optimal factor is P1, the optimal range of P1 for 4–5 mm, P3 for 4–5 mm, and P5 for 2.5–3 mm.

Table 5. Calculation results of peak polar deviation of backrest force values.

Items	Level	P1 Seat Support Strip Thickness (mm)	P3 Backrest Strip Thickness (mm)	P5 Seat Panel Thickness (mm)
K-value	1	1396.8	1440.4	1439.5
	2	1444.2	1440.5	1443.1
	3	1493.6	1453.7	1452
K _{avg} value	1	465.6	480.1	479.8
	2	481.4	480.2	481.0
	3	497.9	484.6	484.7
Best level		3	3	3
R		32.3	4.5	4.9

3.1.3. Analysis of Peak Polarity of Seating Surface Force Values

Seat surface force peak range calculation results are shown in Table 6; the seat surface support strip, backrest strip, and seat panel of the range were 71.3, 7.2, and 12.8, which can be obtained on the overall displacement of the influence of the factors arranged from large to small: P1 > P5 > P3. Compared with the same factor at different levels of the average value “k”, this can be obtained from the different levels of the impact of the indicators of the magnitude. By looking at the trends Figure 1, the following conclusions are drawn: for the peak backrest force, the optimal factor is P1, the optimal range of P1 for 4–5 mm, P3 for 3.5–4.5 mm, and P5 for 2.2–3 mm.

Table 6. Calculation of peak extreme differences in seat surface force values.

Items	Level	P1 Seat Support Strip Thickness (mm)	P3 Backrest Strip Thickness (mm)	P5 Seat Panel Thickness (mm)
K-value	1	3449.5	3552.1	3544.8
	2	3576.5	3573.6	3561.6
	3	3663.2	3563.8	3583.1
K _{avg} value	1	1149.8	1184.0	1181.6
	2	1192.2	1191.2	1187.2
	3	1221.1	1187.9	1194.4
Best level		3	2	3
R		71.3	7.2	12.8

The above range analysis method can be roughly derived from the optimal range of values of P1, P3, and P5, the range of the three factors for trade-offs, and ultimately

determined that P1 is determined in the 4~5 mm, P3 is determined in the 4~5 mm, and P5 is determined in the 2.4~3 mm. By analyzing the key parameters that affect performance based on the actual usage scenarios of the product or system, determining the factors that need to be considered, combining production processes and material characteristics, and finally combining industry standards, customer needs, etc., a reasonable range of parameter values is determined. The next step of optimization is carried out.

4. Finite Element Optimization

Draw the 3D model of the airport waiting chair frame using NX2312. Among them, the lateral support strip can be divided into three areas such as the back, seat surface, and front end of the seat. This study has determined the optimal range of values for P1, P3, and P5, designed with a lightweight approach: “reducing costs while ensuring performance”. The optimization data are set at the maximum values of 5 mm and 3 mm within the optimal range. This “worst-case” optimization method can improve the robustness and risk resistance of the calculation, as well as enhance the universality and adaptability of the calculation results. The external dimensions are 420 mm × 504 mm × 600 mm, in which the thickness of the seat surface support strip and the backrest strip is both 5 mm, and the thickness of the seat panel is 3 mm. The model is then imported into ANSYS Workbench 2022 R1 in x_t format to perform the static analysis to achieve the purpose of lightweight [42].

4.1. Pre-Optimization Testing

Follow the following steps to optimize the analysis:

- (1) Grid division affects the accuracy of the results, computational efficiency, numerical stability, and multi-scale analysis. Reasonable mesh division can improve the accuracy and efficiency of the calculation. In this paper, the model is divided into the hexahedral free mesh, the overall mesh size is set to 5 mm, the mesh encryption of the curvature region and the predetermined stress point is 2 mm, and the total number of the model is 71,224 cells and 238,897 nodes after the division is completed.
- (2) Static analysis of the product can assess the structural strength, optimize the design, save cost and time, predict the product life, and support decision-making and verification. Through static analysis, we can see the deformation of the product under force, displacement, etc. When exploring the application of periodically varying loads, transient dynamics analysis can be applied, but in this paper, the application is static structural analysis, in which acceleration does not affect the results, so the equations can be simplified as follows (1):

$$[K]x = F \quad (1)$$

$[K]$ is the stiffness coefficient matrix, and x is the node displacement. f is the load.

The equivalent stress cloud diagram after solving is shown in Figure 3a; it can be seen that the maximum equivalent stress borne by the main frame is 1074.3 MPa, which appears as a stress singularity, which is an extreme phenomenon to be excluded. According to the basic theory of material mechanics, the normal maximum stress point for the probe detection value of 60.394 MPa; compared with the maximum material yield strength of 235 Mpa for structural steel, there is a lot of optimization space. According to the total deformation of Figure 3b, it can be seen that the maximum deformation of the backrest is 4.8871 mm, and the maximum deformation of the seat surface is 2.2682 mm, which all appeared in the contact point of the model and the mechanical testing machine, which is in line with the experience of the mechanical machine test. From the above values, there is a lot of room for improvement in structural optimization.

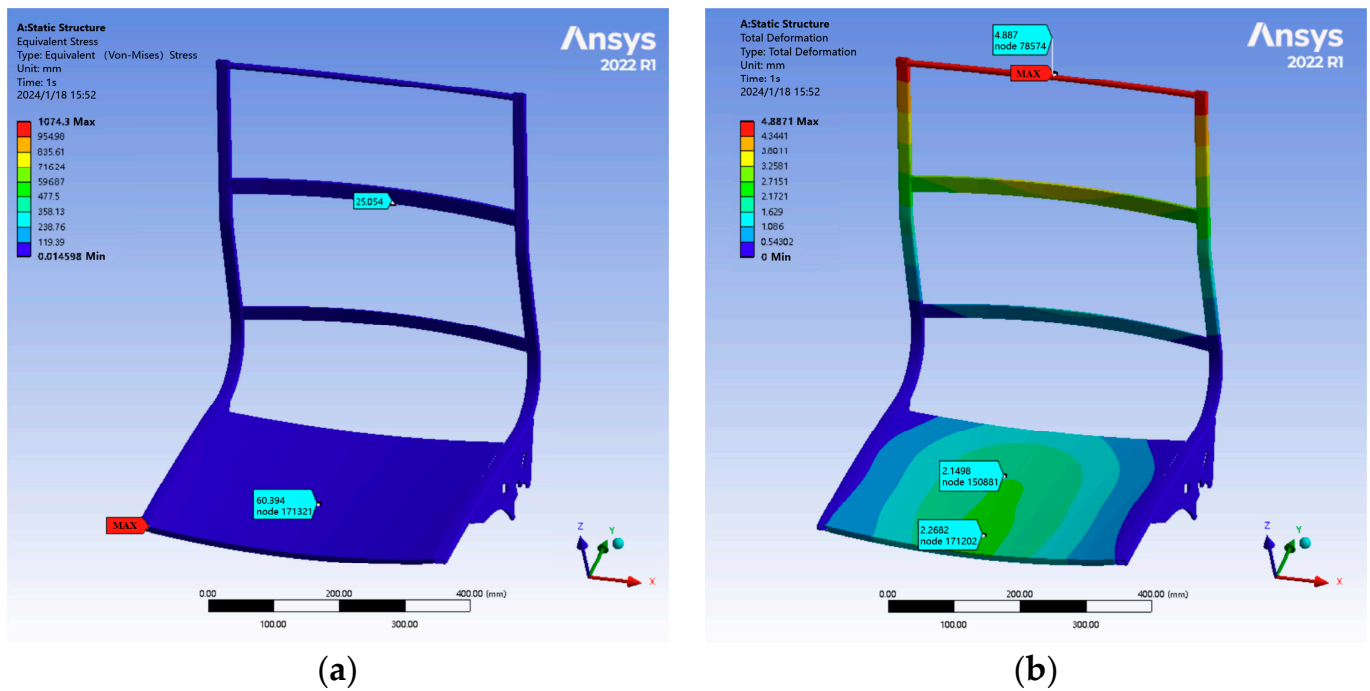


Figure 3. (a) Equivalent force diagram. (b) Total deformation.

4.2. Size Optimization

In structural optimization, performance can be further optimized by fine-tuning the dimensions of the structure. By minimizing the use of materials while maintaining the structural strength and stiffness, a practical and feasible design solution is ultimately obtained. In this paper, they are defined in the Design Modeler plate of ANSYS Workbench, which are P1 (seat surface support bar), P3 (backrest bar), and P5 (seat panel). For the design of output parameters, including constraints and objective function, P6 (equivalent force) and P7 (maximum deformation) are selected as constraints, and P8 (geometric mass) is selected as the objective function. The upper limit of the magnitude of the values is the original value, the lower limit is the range suggested by the mechanical tests in Chapter 3, and the following optimized mathematical model (2) is established.

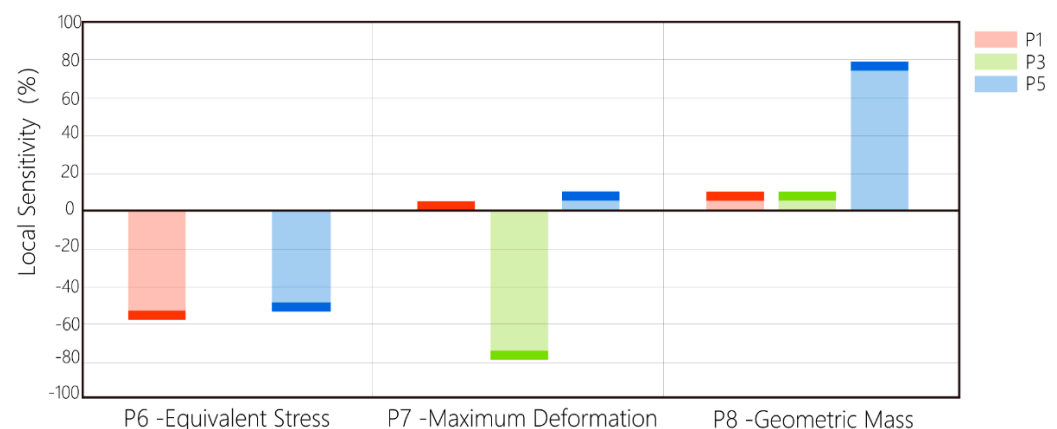
$$\begin{cases} \text{Min.} F(x) \\ X = [x_1, x_2, x_3, x_4] \\ 5\text{t.}4 \text{ mm} \leq P1 \leq 5 \text{ mm} \\ 4 \text{ mm} \leq P3 \leq 5 \text{ mm} \\ 2.4 \text{ mm} \leq P5 \leq 3 \text{ mm} \\ \sigma_{\max} \leq 235 \text{ MPa} \end{cases} \quad (2)$$

Through the experimental design, P1, P3, P5 with P6, P7, P8 are set for the test, and according to the numerical setting of the above mathematical model, the system is designed 15 groups of models for the experiment, and the data will be updated to get Table 7.

In order to further explore the relationship between the factors, response surface sensitivity analysis is used to evaluate the degree and importance of design variables on the objective function, to help determine the design variables that should be focused in the optimization process, exclude variables that have less influence on the objective function, and reduce computational complexity. The global sensitivity analysis diagram is shown in Figure 4 [43–45].

Table 7. Design model experimental data.

Serial Number	P1/mm	P3/mm	P5/mm	P6/MPa	P7/mm	P8/kg
1	4.5	4.5	2.7	1322.9	4.9371	7.7513
2	4	4.5	2.7	1493.1	4.9355	7.7058
3	5	4.5	2.7	1197.1	4.9373	7.7968
4	4.5	4	2.7	1322.7	4.9241	7.7052
5	4.5	5	2.7	1322.7	4.8818	7.7974
6	4.5	4.5	2.4	1440.5	4.9326	7.3989
7	4.5	4.5	3	1165.1	4.9411	8.1037
8	4.0935	4.0935	2.4561	1565.8	4.9246	7.3903
9	4.9065	4.0935	2.4561	1303.5	4.9266	7.4643
10	4.0935	4.0965	2.4561	1565.6	4.8681	7.4652
11	4.9065	4.0965	2.4561	1303.4	4.8712	7.5393
12	4.0935	4.0935	2.9439	1350.1	4.9325	7.9633
13	4.9065	4.0935	2.9439	1127.2	4.9335	8.0373
14	4.0935	4.0965	2.9439	1349.8	4.8754	8.0382
15	4.9065	4.0965	2.9439	1127.1	4.8782	8.1123

**Figure 4.** Global sensitivity analysis diagram.

As can be seen from Figure 3, for the output model geometric quality P8 and P1, P3 and P5 are proportional to the relationship; this is because the thickness increases the model quality increases, and from the sensitivity point of view, the model quality of the most sensitive is P5, sensitivity coefficient of 79.37; followed by P1 with a sensitivity coefficient of 10.377; and the sensitivity of the P3 ranking third, with a sensitivity coefficient of 10.253. The reason for this is because the P5 seat panel accounted for the overall quality being higher, so the degree of sensitivity is higher, and the model quality of the three parameters of the sensitivity of $P5 > P1 > P3$. For the P7 maximum deformation to see the sensitivity of the three parameters is different, P1 and P5 show a positive correlation; P3 shows a negative correlation, in which the sensitivity of the P1 is 4.2496; the sensitivity of the P5 is 10.214; the sensitivity of the P3 is -8.285 ; and the maximum deformation of these three parameters is ranked as $P5 > P1 > P3$, while for the P6 equivalent force to see the effect of the three parameters also shows negative correlation, of which the sensitivity of P1 is -56.78 , the sensitivity of P5 is -52.843 , the sensitivity of P3 is -0.071 , and close to 0 value can be ignored, indicating that P3 has little effect on it. The ordering of maximum deformation on these three parameters is $P1 < P5 < P3$.

In this paper, Design Explorer in ANSYS Workbench is used to optimize the design, and regression analysis is used to establish the fitted functional relationship. After changing the display to 3D, the optimized values of the output variables can be sought from the response surface based on the functional relationship. From Figure 5a, it can be seen that P8 is affected by both P1 and P3, showing a linear increase, with the maximum value reaching

7.84 kg. From Figure 5b, it can be seen that P7 is affected by both P1 and P5 showing a nonlinear change, peaking at 2.92 mm in the seating panel, and then showing a slow growth trend. However, the overall positive correlation is shown with a maximum value of 4.94 mm.

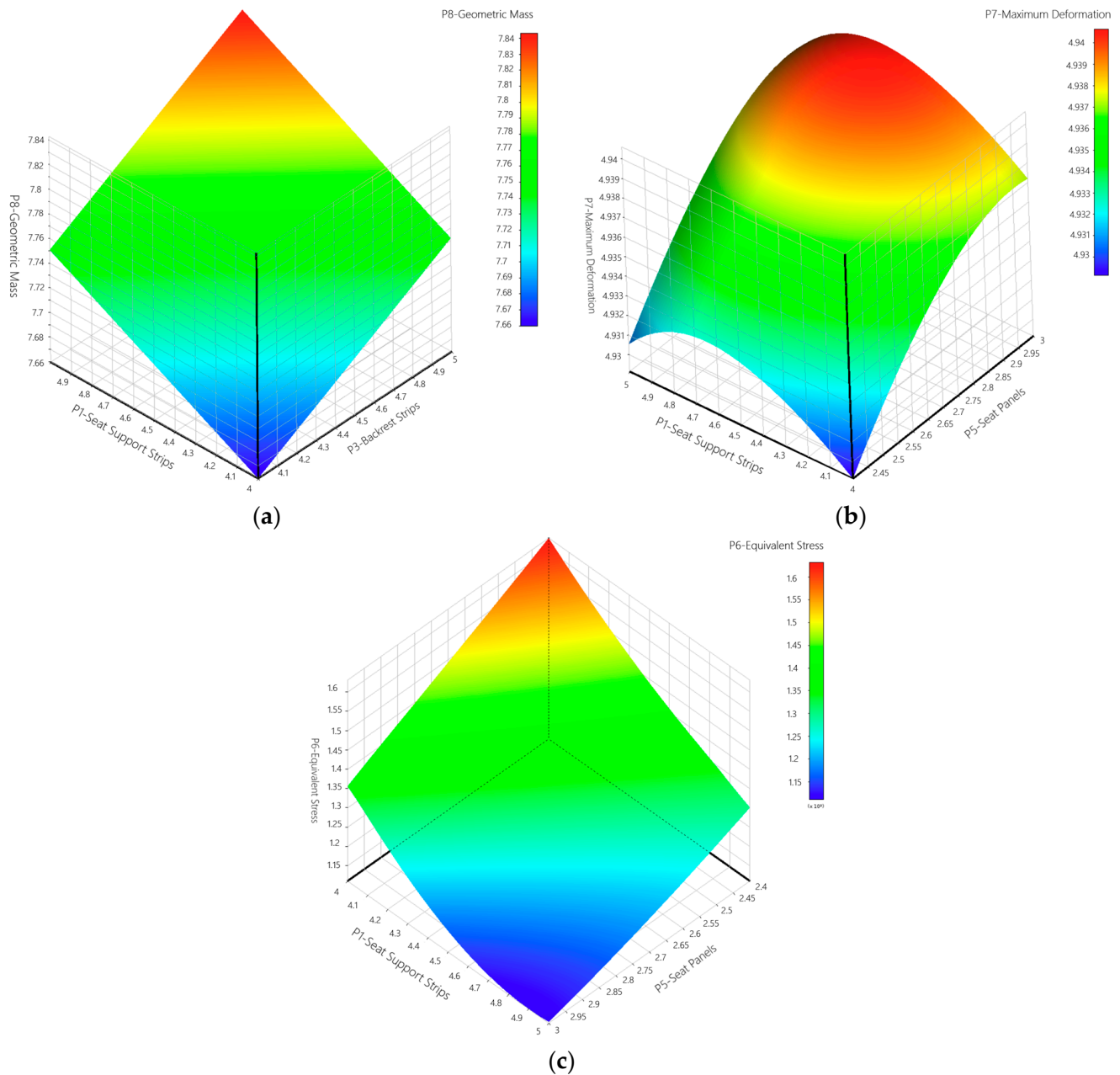


Figure 5. (a) Effect of parameters P1 and P3 on geometric quality. (b) Effect of parameters P1 and P5 on maximum deformation. (c) Effect of parameters P1 and P5 on equivalent stresses.

From Figure 5c, it can be seen that P6 is also simultaneously subjected to changes in P1 showing a nonlinear change, with an overall positive correlation, increasing as P1 and P3 decrease, with a maximum value of about 1.6 mm. From the above analysis, it can be seen that the rate of change of the parameter is similar to its rate of increase, and the relationship between the change of the output parameter and the input parameters P1, P3, and P5 is consistent with the results of the sensitivity analysis.

The impact of various size parameters on the chair's performance may be ascertained from the response surface analysis presented above. This aids in determining the best mix

of sizes that will allow the design objectives to be satisfied while maintaining stability and safety. The optimized design solution that minimizes the model mass P8 is extracted from the optimized design results based on the lightweight design aim. The original solution and this optimized design solution will be compared; the details of that comparison are displayed in Table 8.

Table 8. Comparison before and after dimensional optimization.

Variant	P1 Thickness of Seat Surface Support Strip/mm	P3 Thickness of Backrest Strip/mm	P5 Thickness of Seat Panel/mm	P6 Maximum Equivalent Force/MPa	P7 Maximum Deformation/mm	P8 Geometric Mass/kg
Original Program System	5	5	3	1074.3	4.8871	8.1953
Optimization Program Selected Solution	4.5	4	2.7	1322.7	4.9241	7.7052
	4.5	4.5	2.7	1322.9	4.937	7.7513

This set of parameters will also be displayed in Table 8. However, considering the high accuracy of the thickness in the optimization plan, if the thickness of P3 is reduced to 4 mm, the structure of the seat will become loose in subsequent experiments. Therefore, considering practical applications, we need to choose a set of data with moderate input and output parameters as the final choice for size optimization. This set of parameters will also be displayed in Table 8.

From Table 8, it can be observed that the selected lightweight design solution increases the maximum equivalent force by 23.14% compared to the original solution; although the increase in maximum equivalent force is large, it is still within the acceptable range. The maximum total deformation increased by 1.02%. In addition, the selected solution succeeded in reducing the model mass by 0.444 kg, and for the whole model mass the reduction amounted to 8.654 kg, which is a reduction of 5.417%. This result is a desirable result within the controllable range, and successfully achieved the initial lightweight design of multifunctional modular furniture, and there is still room for optimization.

4.3. Topology Optimization

Topology optimization is an engineering design methodology that aims to minimize the mass of a structure, maximize its performance, or satisfy specific design requirements by optimizing the distribution of materials and structural morphology. It is mainly used in structural design fields such as mechanical, aerospace, automotive, architectural, and other engineering fields. In this paper, topology optimization is carried out for the frame of an airport seat to improve on the best solution selected from the above dimensional optimization [46–48].

This article mainly uses the Shape Optimization module in ANSYS Workbench to perform local topology optimization of airport waiting chair frames. Based on the actual usage of airport seats and the finite element analysis results of size optimization, it was found that stress is mainly concentrated on the seat surface and backrest area, and there are details that can be optimized in these areas. On the basis of ensuring seat stability and reducing the amount of steel used in the structure, the mathematical model established can be expressed as (3).

$$\left\{ \begin{array}{l} find \rho = [\rho_1 \rho_2 \dots \rho_n]^T \\ min C(\rho) = U^T K U = \sum_{i=1}^n (\rho_i)^p u_i^T K_0 u_i \\ KU = F \\ s.t. \left\{ \begin{array}{l} V(\rho)/V_0(\rho) \leq 30 \\ 0 \leq \rho_{min} \leq \rho_i \leq 1 \end{array} \right. \end{array} \right. \quad (3)$$

In the mathematical equations, ρ denotes the unit density, ρ_i denotes the relative density of the units, C denotes the objective function, U denotes the system displacement matrix, p denotes the penalty factor of the system, K denotes the system stiffness matrix before the structural optimization, K_0 denotes the unit stiffness matrix before the structural optimization, F denotes the system load vector, u_i denotes the displacement column vector of the structural units, V denotes the volume of the system after the system optimization, V_0 denotes the volume of the system before the system optimization, v_i denotes the volume of the structural unit after the optimization, α denotes the volume coefficients, and ρ_{min} denotes the value of the minimum design variables.

The specific properties of the material are referred to in Table 1. Meshing is performed using Solid186 for solid cells, and the grid cell size is adjusted to give the number of cell nodes as 238,814 and the number of cells as 71,183. The bottom of the foot support is used as the exclusion area, and the rest of the area is the design area, and the want type of the target is set to compliance, and the Target Reduction target is set as 95%. The calculation results are shown in the Figure 6 topological density map, where Figure 6d shows the overall topological density map.

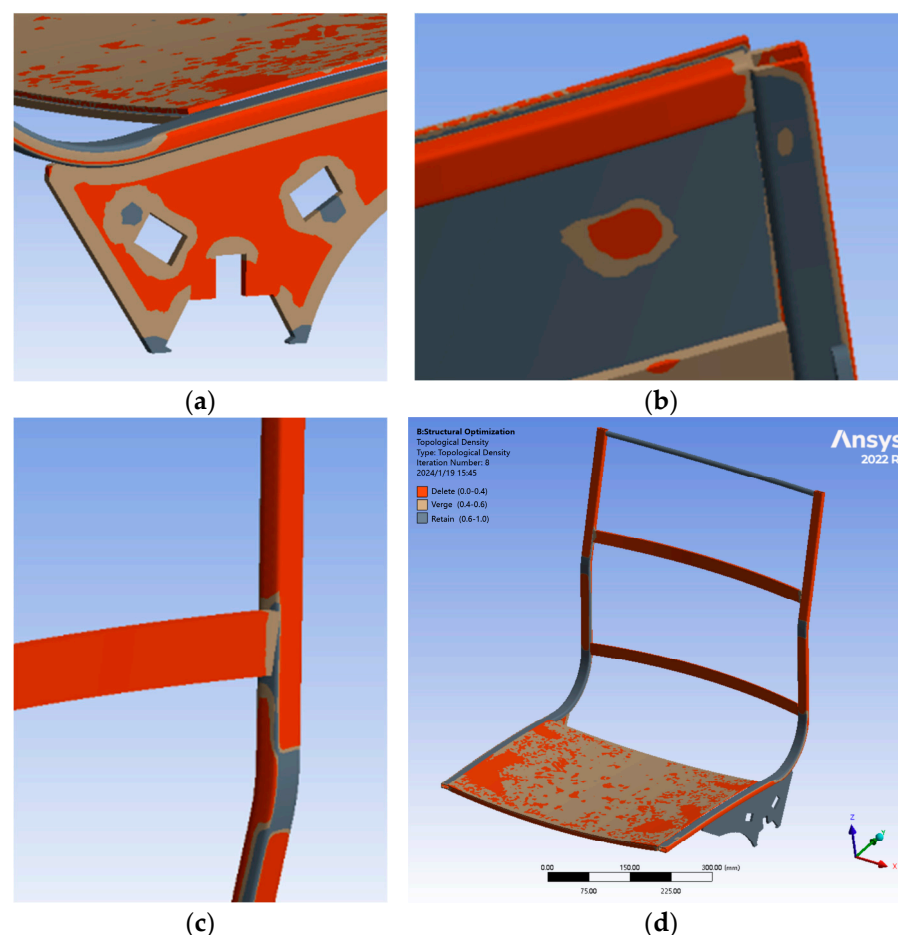


Figure 6. Topological density maps (a–d).

Based on the interpretation of the progress and trends in bending extrusion profile forming, combined with practical applications [49–51], for the density topology map, the overall wild frame can be optimized for lightweight.

- (1) According to Figure 6, we can see that there are more optimizable areas on the seat surface, and we can consider punching holes on the seat surface. This innovative form can increase the contact area between the polyurethane foam material and the frame,

making the connection between the two more secure, thereby improving the service life and stability of the seat, as shown in Figure 7.

- (2) In response to the problem of small curvature at the corners of the seat surface and the high probability of collision for passengers passing by, this study adjusts the four large curvature curves of the seat panel, reducing materials while also improving safety and comfort. The specific part is the location in the red circle in Figure 7.
- (3) The two rectangular holes of the foot support, widening treatment, and the thickness of the bar in the figure reduce the thickness of the bar. The thickness of the seat surface support bar is reduced from 4.5 cm to 4 mm, the thickness of the backrest bar from 4.5 cm to 4 mm, the thickness of the seat panel from 2.7 mm to 2.5 mm, and the thickness of the foot support from 5 mm to 4 mm.

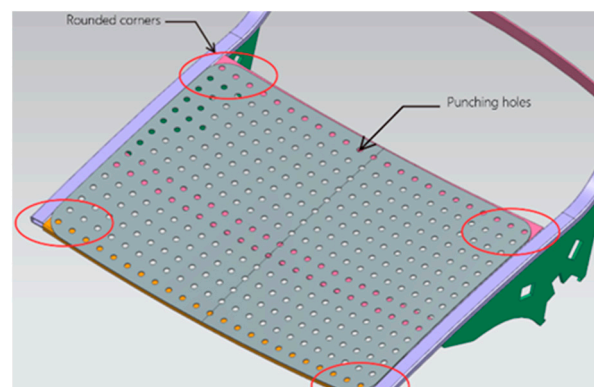


Figure 7. Detailed improvements.

The maximum stress, maximum deformation, safety factor, and mass change of the airport waiting chair frame before and after improvement are shown in Table 9 below. The maximum deformation is 5.5726 mm, which is an increase compared to the pre-improvement, but the value is still within the acceptable range. The maximum stress of the airport seat frame after improvement is 744.1 MPa, but when checking the maximum value, it is found that there is a stress singularity, so it is tested the size of its key points, in which the maximum stress of the seat surface is 164.26 MPa, the symmetry point is 182.41 MPa, and the value of the maximum stress point of the backrest is 40.053 MPa, which is less than the yield limit of the structural steel, which is 235 MPa. The safety coefficient is 1.288, which meets the structural requirements. The model mass of 8.1953 kg becomes 5.3433 kg, which reduces the amount of steel used by 2.842 kg, a reduction of 34.8%. The purpose of lightweighting is achieved [17,52,53].

Table 9. Changes in parameters before and after optimization of the airport waiting chair frame.

	Maximum Stress/MPa		Maximum Deformation/mm		Safety Factor		Mass/kg	
	Before	After	Before	After	Before	After	Before	After
Numerical value	1074.3	744.1	4.8871	5.5726	3.85	1.288	8.1953	5.3433

5. Sustainability

Sustainability is a comprehensive concept that refers to meeting the needs of the present without compromising the ability of future generations to meet their needs. Nowadays, the steel industry accounts for 7% of global carbon dioxide emissions, and in the past 10 years, for every ton of steel produced, 1.83 tons of carbon dioxide were emitted. However, for the steel industry, as one of the largest sources of carbon emissions in the world, how to combine with the concept of sustainable development is a great challenge [54–56]. The lightweighting of the airport waiting chair frame in this paper provides an answer to

this, and this study is a good integration of environmental sustainability and economic sustainability, as seen in Figure 8, which shows the full process flow diagram of an airport waiting chair, which includes product design, raw material extraction and processing, manufacturing production, packaging and transportation, sales and use, and end-of-life and recycling. This study is based on the first design link optimization, successfully reducing the amount of steel, single in the frame reduction of 34.8%, which significantly reduces the environmental load of raw material extraction and processing. This is a huge contribution to the carbon footprint of manufacturing as a whole.

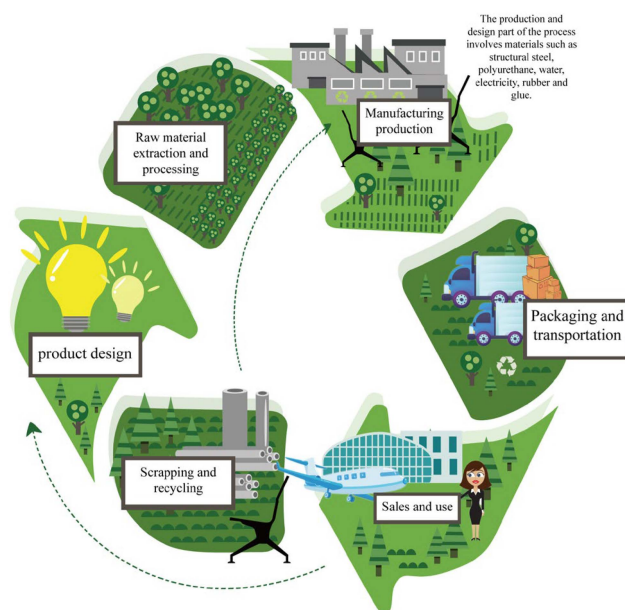


Figure 8. The whole production process of airport waiting chairs.

This study is in line with and supports the international community's current emphasis on an urgent need for sustainable development, as China has proposed that it "will increase the strength of its national autonomous contribution, adopt more vigorous policies and measures, strive to peak carbon dioxide emissions by 2030, and endeavor to achieve carbon neutrality by 2060" [57]. The study is in line with and supports the current international community's emphasis on sustainable development and urgent needs. The specific lightweight design initiatives of this study are as follows: make the chair lighter in overall weight and lower energy consumption during transportation and loading and unloading, while the reasonable structural design can improve the strength and stability of the chair, extend the service life of the product while reducing carbon emissions and energy consumption in all aspects, ultimately achieve the goal of environmentally friendly products, and ultimately also form a closed loop of recycling. According to the survey, this is of great significance in realizing the goal of global carbon neutrality. In the future, these energy-saving and carbon-reducing technologies and concepts will be progressively applied to more manufacturing industries, making due contributions to the fight against climate change. This is a good idea for expansion. Lightweight design has a broad application prospect in the field of public space furniture and is of great significance to the realization of broader sustainable development goals. It will contribute to the realization of green and low-carbon development.

6. Conclusions

After mechanical testing and structural optimization of airport waiting seat frames, the following conclusions are drawn:

- (1) Through the mechanical testing of nine different sizes of the airport waiting seat frames, the optimal range of optimization of the dimensions of the three parts of the

seat surface support strips, the backrest strips, and the seat panels were derived by combining the analysis of the polar analysis method and the JMP diagram.

- (2) The static analysis of the frame using ANSYS Workbench yields a large deformation of the frame's seat panel and the transverse support strip at the backrest, with the maximum equivalent stress and maximum displacement meeting the design requirements, the stress value of the overall frame is small, and the stress in the critical parts is less than the maximum material yield strength of the structural steel, which indicates that there is a lot of room for optimization.
- (3) The mathematical model 2 of dimensional optimization and mathematical model 3 of topological optimization are established with the minimum mass of the frame as the optimization objective, and the maximum equivalent force and total deformation as the constraints.
- (4) The mass of the frame after size optimization and topology optimization is changed from 8.1953 kg to 5.3433 kg, which is 34.8% less than the previous one, and it is inspected to fully meet the product performance and use standards, which meets the requirement of lightweight. The maximum stress of the frame is reduced, and the safety coefficient is within the specified range. The structural optimization method of the airport waiting chair frame can provide a reference for the structural optimization of other geometrical frames with complex geometry and multi-directional loads.

The structural optimization method of the airport waiting chair frame provides a valuable reference for the structural optimization of other geometric frames with complex geometries and carrying multi-directional loads. The potential errors in the design of the airport waiting chair frame may mainly include the following points. 1. Inaccurate estimation of parameters such as load and stress may occur, resulting in the unreasonable selection of frame size and materials. We can conduct sensitivity analysis on key parameters and set a reasonable safety factor. 2. If the joint design is improper, we can optimize the joint shape, reduce the stress concentration factor, or take measures such as transition arcs to relieve stress. 3. Inaccurate judgment of material strength, stiffness, fatigue characteristics, and other parameters may lead to safety hazards. We can choose materials with reliable quality and conduct actual experimental verification. Overall, this structural optimization approach can guide designing lighter, more material-efficient products and play an active role in reducing resource consumption and improving energy efficiency. By applying optimization techniques to product design, we can promote sustainable development and achieve effective use of resources and environmental protection. In summary, the lightweight design of the airport waiting chair frame involved in this study brings a series of practical advantages in terms of manufacturing and cost. These advantages are particularly prominent when applied on a large scale. The frame of a seat reduces the use of 2.842 kg of steel, which can significantly reduce costs and increase profit margins during large-scale production. It has significant advantages when winning a project bid, which is beneficial for both enterprises and the entire industry, as well as promoting the popularization and application of related products.

In the subsequent optimization design, we can consider optimizing the curves and angles of the seat through ergonomic principles to provide better support and reduce pressure. For the selection of materials for the frame, materials such as wood and carbon fiber can also be considered. Scholars can further explore the stability and lightweighting of frame structures under different materials. In addition, the optimized airport waiting chair frame can be considered to adapt to different use scenarios and cope with special situations. Multifunctional integration can also be considered, such as integrating power, lighting, communication, and other functions into the framework structure to increase the added value of the product. Modular interfaces for easy upgrading and customization of functionality can be designed in the later stages. From a sustainability perspective, in material selection and structural design, the environmental impact of the entire product lifecycle is fully considered to improve recyclability. The use of renewable energy-driven functional modules can be explored to enhance the green attributes of products. The design

concept of this study is not limited to airport waiting furniture but can be applied to other public places to explore the application potential in other industry fields, such as aviation, military equipment, and other scenarios with higher demand for lightweighting, to promote the further development and application of related products.

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