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Analysis Method and Case Study of the Lightweight Design of Automotive Parts and Its Influence on Carbon Emissions

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Abstract: The automobile industry, as a representative in pursuing the goals of "emission peak" and "carbon neutrality", has made low carbon a new industrial practice. With regard to low carbon, the lightweight design proves to be an effective approach to reducing carbon emissions from automobiles. Given the state of research, in which the existing lightweight design schemes of automobiles seldom consider the impact of the lightweight quality on carbon emissions during the whole life cycle of the automobiles, this paper proposes a more comprehensive lightweight design method for automobiles in regard to carbon emissions. First, the finite element method was adopted to analyze the stress, strain and safety factors of the automobile parts based on their stress, so as to identify the positions where the lightweight design was applicable. Subsequently, a lightweight scheme was designed accordingly. Next, the finite element method was re-applied to the parts whose weights had been reduced. In this way, the feasibility of the lightweight scheme was verified. In addition, a method of calculating the carbon emissions produced by changes in the mass, manufacturing processes, application and recycling of automobile parts after the application of the lightweight design was also presented. The method can be used for evaluating the low carbon benefits of the lightweight design scheme. To prove the feasibility of the method, the ZS061750-152101 wheel hub designed and manufactured by Anhui Axle Co., Ltd. was taken as an example for the case analysis. The lightweight design changes three structures of the wheel hub, reducing its weight by 1.4 kg in total. For a single wheel hub, the carbon emissions are reduced by 51.22 kg altogether. That is to say, if the lightweight scheme were to be applied to all the wheels produced by Anhui Axle Co., Ltd. (about 500,000 per year), the carbon emissions from the wheel production, application and recycling could be cut by 2.56×10^7 kg, marking a favorable emission reduction effect. The proposed method can not only provide insight into the lightweight design of automobiles and other equipment against the background of low carbon but also provide a channel for calculating the carbon emission changes in the whole process after the application of the lightweight design.

Keywords: lightweight; carbon emissions; low carbon benefits; optimization design; wheel hub

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1. Introduction

In recent years, automobile production and sales have continued to rise at high rates, resulting in the fast growth of automobile ownership [1]. On the one hand, this phenomenon brings enormous development opportunities to the automobile industry and related industries. On the other hand, it incurs various challenges [2,3], such as environmental problems caused by greenhouse gas emissions and resource depletion induced by energy consumption [4]. The energy saving and emission reduction of automobiles have become a focus of the automobile industry [5]. The question of how to incorporate a low-carbon design of automobiles so as to develop them into internationally certified low-carbon products, keep pace with the trends of the consumer market and seize the green automobile consumption market has become the long-term development strategy of automobile manufacturing enterprises [6]. The "Made in China 2025" initiative stated specific demands for the lightweight quality of automobiles, including the realization of the lightweight property of automobile parts and optimization of the structure of automobiles [7]. Therefore, applying a low-carbon design to automobiles is essential for minimizing the negative impact of automobile manufacturing on the environment and improving the environmental friendliness of automobile products. Specifically, such an aim can be realized by supporting the low-carbon design and manufacturing of automobile products, quantitatively assessing the carbon emissions of their typical parts in the early stage of the design and optimizing their carbon emission performance through structure design and favorable processes.

In terms of the lightweight design, scholars generally rely on structure design, advanced manufacturing processes and new materials to reduce the weight of automobile parts. To name a few, Baskin et al. [8] applied the variable density topology optimization technology to the body-in-white development process. The application accomplished the lightweight property of the automobile while ensuring the enhancement of its various performance aspects. Shimoda et al. [9] adopted the parameter-free shape optimization method to redesign the shape of the weight-reducing hole of the main bearing beam of the automobile from the perspective of strength constraint, which successfully reduced the weight of the structure. Gauchia et al. [10] employed the genetic algorithm to optimize the key dimensions of the bus body, effectively reducing its weight and strengthening its torsional stiffness. Xiao et al. [11] suggested a multi-objective optimization method based on programming work for steel wheels, in which the design variable is the thickness of the spoke. Xiao et al. [12] built a static and dynamic multi-objective topology optimization mathematical model for spokes by utilizing the compromise programming method. With the aid of this model, Xiao et al. performed topology optimization on the spokes when they were running under bending fatigue conditions, which realized the lightweight quality of the hubs. Zhang et al. [13] performed single-objective topology optimization on aluminum alloy wheel spokes using the variable density topology optimization method. Pang et al. [14] established a response surface model between dimensions and structural properties of the spokes and hubs for the purpose of parameter optimization to achieve the lightweight property. Hu et al. [15] optimized the parameters of a certain type of aluminum alloy wheel hub by regarding the thicknesses of the wheel and the rim as the design variables and the minimum mass of the wheel as the goal. Chai et al. [16] designed a lightweight wheel hub formed of a composite whose thermoplasticity was enhanced using long glass fiber and studied its fatigue life by means of simulation and experiments. Yi et al. [17] pointed out that compared with the aluminum alloy hubs, the green effect produced by magnesium alloy hubs is mainly due to the reduction in fuel consumption caused by weight loss. With respect to the carbon emissions of automobiles, Zhang et al. [18] studied the design process of automobile engines. From the results of the analysis of the integrated system, their study reported that the raw material procurement stage of the engine leads to the largest amount of carbon emissions, with the cylinder block being the chief contributor. Based on the established evaluation model, they also proposed optimizations for the structure and materials and verified the feasibility of the integrated system. Hao et al. [19] established a bottom-up model to consider the energy and environmental impacts of reducing greenhouse gas emissions from a passenger vehicle fleet. Wu et al. [20] investigated the identification of barriers, analysis and solutions for hydrogen fuel cell vehicles designed for deployment in China with the goal of carbon neutrality. Du et al. [21] conducted a study that focused on policy making and its impact on the automotive industry in the context of carbon neutrality. Du et al. [22] investigated the costs and potential of reducing CO_2 emissions in the Chinese transportation sector by means of energy system analysis. Jhaveri et al. [23] developed a parametric life cycle model to assess the life cycle performance of TWDCI compared to conventional cast iron and cast aluminum in terms of energy (MJ) and GHGs (as carbon dioxide equivalents: kg CO_2e).

In summary, the lightweight design of automobile parts is often accompanied by the optimization of their shapes and sizes. However, the optimization scheme can only be obtained through an iterative search based on a rigorous mathematical model, which proves to be a cumbersome process. As a consequence, there is an urgent need to establish a popular, simple and practical lightweight optimization method for automobile parts. Meanwhile, in terms of automobile carbon emissions, scholars have mostly focused on calculating the total carbon emissions of the automobile industry, attached importance to technologies concerning carbon emission reduction and investigated the impacts of carbon policies on the automobile industry. Unfortunately, limited attention has been devoted to automobile carbon emissions in the initial design and optimization of automobile parts.

After the weight of automobile parts is decreased, some manufacturing processes will inevitably be added, which will certainly result in extra carbon emissions. This begs the questions: how can we calculate the reduced carbon emissions resulting from the decreased mass and the newly increased carbon emissions arising from the additional processes, and what are the comprehensive carbon emission benefits of the two?

To answer the above questions, this paper proposed a lightweight design method for the carbon emissions of automobile systems. The specific research scheme is described as follows: First, the finite element method was adopted to analyze the stress, strain and safety factors of the automobile parts based on their stress, so as to identify the positions where the lightweight design was applicable. Subsequently, a lightweight scheme was designed accordingly. Next, the finite element method was re-applied to the parts whose weights had been reduced for the purpose of analyzing their stress, strain and safety factors. In this way, the feasibility of the lightweight scheme was verified. In addition, a method for calculating the carbon emissions of automobile parts with lightweight scores was also presented, through which the variation in the carbon emissions produced by the mass reduction, manufacturing processes, application and recycling of the parts could be measured. Based on these data, the low-carbon benefits of the lightweight scheme were comprehensively evaluated. Moreover, the ZS061750-152101 wheel hub designed and manufactured by Anhui Axle Co., Ltd. was taken as an example for the case analysis. The lightweight design changes three structures of the wheel hub, reducing its weight by 1.4 kg in total. The carbon emissions resulting from the saved material, changed manufacturing processes and application and recycling of the parts are reduced by 51.22 kg altogether. That is to say, if the lightweight scheme were to be applied to all the wheels produced by Anhui Axle Co., Ltd. (about 500,000 per year), the carbon emissions from the wheel production, application and recycling could be cut by 2.56×10^7 kg, marking a favorable emission reduction effect.

This study provides both theoretical and practical contributions. In theory, on the basis of its structural analysis, the modal, fatigue strength and life of the hub were simulated using the finite element method, and the lightweight design of the hub was verified. This method provides a useful reference for the lightweight design of automotive parts. In engineering practice, this method can clearly inform the engineering designers about how to efficiently and quickly lighten the mechanical parts of the automobile and to calculate the reduced carbon emissions resulting from the decreased mass and the newly increased carbon emissions arising from the additional processes. It can improve the structure, save materials, reduce the production costs, shorten the design cycle and meet the low carbon demands of customers for manufacturing enterprises.

The remaining content of this paper is arranged in the following manner: A lightweight design method for the carbon emissions of automobile systems is provided, and the low carbon benefits of the lightweight scheme are comprehensively evaluated in Section 2. The ZS061750-152101 wheel hub designed and manufactured by Anhui Axle Co., Ltd. is taken as an example for the case analysis, and a comparative analysis of the mechanical properties of the wheel hub before and after the lightweight design and an analysis of the emission reduction benefits after the lightweight design are presented in Section 3. The main innovations are as follows: This study proposed a lightweight design method for the carbon emissions of automobile parts considering the reduction in carbon emissions arising from the mass reduction, manufacturing process and recycling. The carbon emission benefits of each link caused by lightweight design were considered and calculated.

2. Method

2.1. Flowchart of the Method

We built a lightweight design method for the carbon emissions produced in the automobile life cycle. Specifically, the finite element method was adopted to analyze the stress, strain and safety factors of the automobile parts based on their actual stress and obtain the corresponding contours. Afterwards, the positions with the lowest stress and strain and the largest safety factors were identified on the basis of these contours, which are crucial for the determination of the positions that can achieve the lightweight property. Then, considering the actual working conditions of the parts, a lightweight solution was proposed. After the implementation of the scheme on the parts, the finite element method was re-applied to the lightweight parts to explore their changes in stress, strain and the safety factor, as well as the mechanical properties, hence verifying the feasibility of the lightweight scheme. Finally, the variations in the carbon emissions caused by the mass reduction, manufacturing processes, application and recycling of the parts were calculated to evaluate the carbon emissions generated by the lightweight design and assess the low carbon benefits. The flowchart of the proposed method is presented in Figure 1.

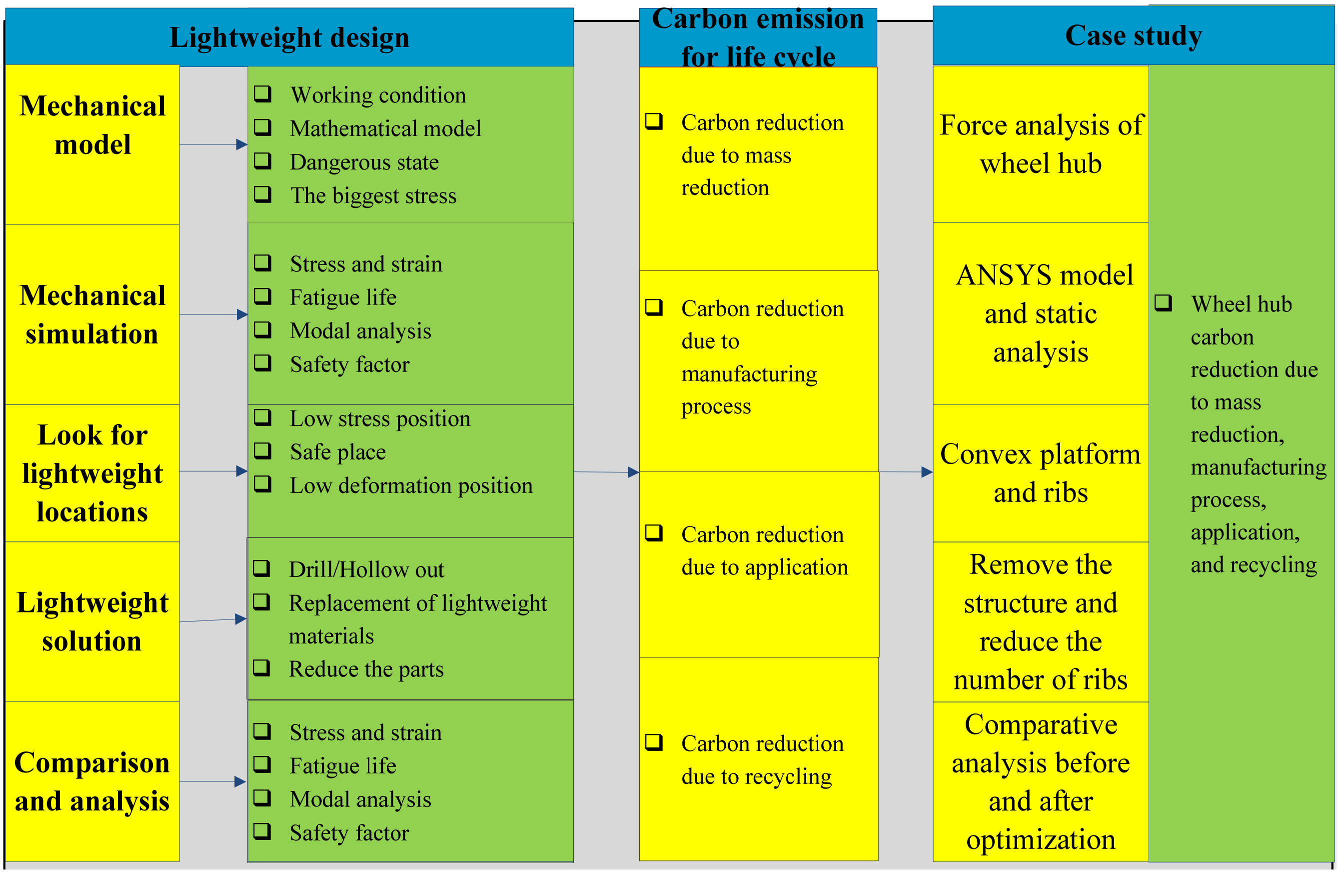


Figure 1. Flowchart of the proposed lightweight design method for carbon emissions.

2.2. Finite Element Analysis and Lightweight Scheme

The primary research object of this study is the automobile industry. Considering that the stress states of automobile parts vary significantly due to their abundant types, we conducted finite element analysis in accordance with the actual stress state. The procedure of the analysis is described as follows:

(1) Build the 3D model. According to the actual parameters of the part, the 3D modeling software is used to establish the 3D model of the part.

(2) Import the 3D model into the finite element software (ANSYS). Convert the format of the 3D model (generally, prt, sldprt, etc.) to the format that can be recognized by the finite element analysis software (generally stl, igs, stp, etc.).

(3) Apply the materials. Select materials in the material library of the finite element analysis software or add material attributes as needed to define the materials.

(4) Perform meshing: The higher the node number and the cell number are, the more accurate the calculation results will be, but more computation time will be required. The grid size needs to be selected or divided according to the actual application requirements.

(5) Add the constraint. According to the actual constraint status of the components, simulate their constraint status in the software and add appropriate constraints according to the actual situation

(6) Add the loads. Simplify the actual stress state through force analysis and add forces, pressures and other loads that can be simulated in the software.

(7) Simulation calculation. Set the simulation step size, simulation time, etc., as required. After setting the above process, use computers for the solution and post-processing. The cloud diagram of the stress value, shape variables and safety factor of the brake hub in this working environment can been obtained through a simulation calculation.

(8) Identify lightweight positions. Analyze the simulation results to acquire contours of the stress, strain and safety factor of the parts. Afterwards, identify lightweight positions, i.e., positions with the lowest stress and strain and the largest safety factor, according to the above contours.

(9) Design the corresponding lightweight scheme. Design the corresponding lightweight scheme based on the structures and actual working conditions of the parts. In the lightweight design scheme, some materials are removed. For example, holes, chamfers and grooves are added, while the number of ribs and the thickness of the plates are reduced.

The process of finite element analysis and the lightweight scheme are shown in Figure 2.

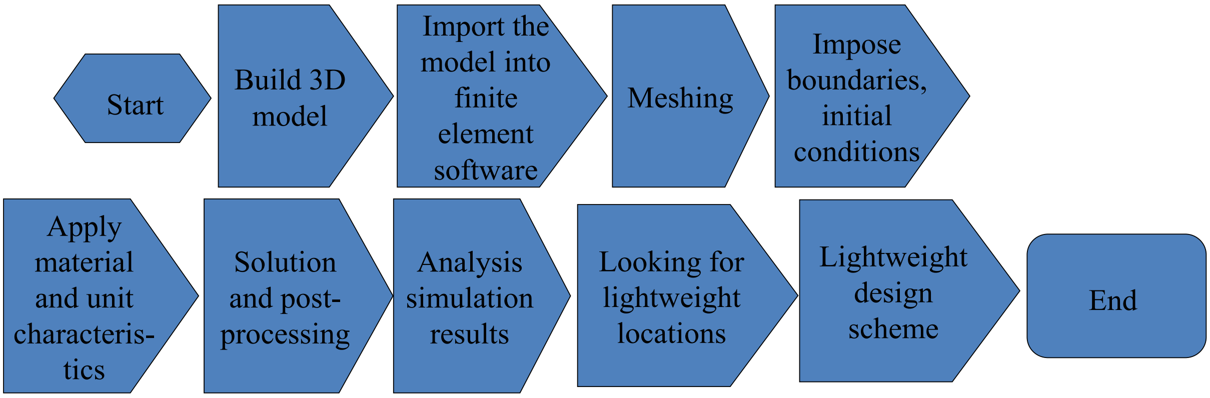


Figure 2. Finite element analysis process and lightweight scheme.

2.3. Comparison and Analysis

A 3D model of the parts developed according to the lightweight design scheme is built. On this basis, the weights of the parts before and after the application of the lightweight design can be compared to reveal whether the mass of the parts is reduced. Then, the above finite element analysis is performed on the parts developed according to the lightweight design scheme to obtain contours of the stress, strain and safety factor of the parts, and the procedure is the same as that stated in Section 2.2. Next, these contours are comparatively analyzed with those acquired prior to the lightweight design to determine whether the stress, strain and safety factor remain within the reasonable ranges.

2.4. Carbon Emissions Caused by the Lightweight Design

The carbon emissions of the parts developed according to the lightweight design are calculated to evaluate the carbon reduction benefits of the lightweight scheme. In particular, the carbon reductions resulting from the mass reduction, manufacturing processes, use and recycling of the parts are calculated.

(1) Carbon emissions from the mass reduction after the lightweight design

After the lightweight design is applied, the mass of the parts is reduced, which means that a smaller amount of raw materials (such as steel and aluminum) are needed. As a result, the carbon emissions produced in the mining and processing of these less-used materials decrease. The decreased carbon emissions can be calculated by Equation (1) [24]. Carbon impact factors are used in this calculation. The carbon emission factor generally refers to the statistical average of the amount of carbon dioxide produced (or emitted) by a unit of production under normal conditions [25]. It can also be converted according to standard coal. The emission factor method is a common method used to calculate carbon emissions based on the empirical emission factors and yields of products:

$$\mathrm{C_{\Delta m}} = \Delta \mathrm{m} \times \mathrm{f_m} \tag{1}$$

where $\mathrm{C_{\Delta m}}$ is the carbon emissions from the lightweight-induced mass reduction, kg; $\Delta \mathrm{m}$ is the reduced mass, kg; and $\mathrm{f_m}$ is the carbon emission factor of the material flow, kg/kg.

(2) Carbon emissions from changes in the manufacturing processes after the lightweight design

The calculation of the carbon emissions produced in the production and processing stages should take all the inputs and outputs involved into account. The former include the inputs of the materials (raw materials, auxiliary materials, etc.) and energy (electricity, coal, natural gas, etc.), while the latter cover the outputs of the energy (electricity and heat) and emissions (gas, waste and liquid waste). Therefore, the carbon emissions of the entire production and processing stages can be calculated from the perspective of the “three flows” (energy flow, material flow and environmental emission flow). The “three-flow” model includes both the direct carbon emissions from material production and processing and the indirect carbon emissions from energy consumption and waste disposal.

The production of the parts generally involves complex processes, each of which emits carbon. Therefore, the material flow consumption M, the energy flow consumption E and the environmental emission flow consumption W in each process i ($i = 1, 2, \ldots, i_0$)) should all be comprehensively considered. The consumptions of the three flows include various types of materials j ($j = 1, 2, \ldots, j_0$), energy k ($k = 1, 2, \ldots, k_0$) and pollutants l ($l = 1, 2, \ldots, l_0$), respectively:

$$C_m = \sum_{i=1}^{i_n} \sum_{j=1}^{j_n} M_i \times f_m^N \tag{2}$$

$$C_e = \sum_{i=1}^{i_n} \sum_{k=1}^{k_n} E_i \times f_e^N \tag{3}$$

$$C_w = \sum_{i=1}^{i_n} \sum_{l=1}^{l_n} W_i \times f_w^N \tag{4}$$

where i, j, k and l are all natural numbers.

The analysis of the material flow, energy flow and environmental emission flow in the production and processing stages reveals that the lightweight design of the parts is accompanied by changes in the processes. Once the processes are changed, the amount of carbon emissions also changes. The carbon emissions resulting from changes in the production and processing stages after the lightweight design can be expressed as:

$$\begin{aligned} C_{\Delta p} &= \Delta C_m + \Delta C_e + \Delta C_w \\ &= -\sum_{i=1}^{i_n}\sum_{j=1}^{j_n} \Delta M_i \times f_m^j - \sum_{i=1}^{i_n}\sum_{k=1}^{k_n} \Delta E_i \times f_e^k - \sum_{i=1}^{i_n}\sum_{l=1}^{l_n} \Delta W_i \times f_w^l \end{aligned} \tag{5}$$

where $C_{\Delta p}$ is the variation in carbon emissions due to changes in the production and processing stages after the lightweight design, kg; C_m is the carbon emissions of the material flow, kg; C_e is the carbon emissions of the energy flow, kg; C_w is the carbon emissions of the environmental emission flow, kg; f_m^N is the carbon emission factor of the material flow, kg/kg; f_e^N is the carbon emission factor of the energy flow, kg/kg; and f_w^N is the carbon emission factor of the environmental emission flow, kg/kg. It should be noted that the negative sign in Equation (5) denotes the negative carbon emissions produced by the additional processes after the lightweight design.

(3) Carbon emissions from the use of the parts after the lightweight design

The application of the lightweight design to the parts can directly influence the carbon emissions of a car. The relationship between the carbon emissions of a car and the reduction in the vehicle mass can be expressed as:

$$\mathrm{C}_l = l\eta_w \Delta m \tag{6}$$

where C_l is the carbon emissions from the vehicle exhaust caused by the application of the lightweight design on the brake hub, kg; η_w is the emission coefficient per kilometer, km^{-1}; and l is the vehicle kilometers traveled, km.

(4) Carbon emissions from the recycling of the parts after the lightweight design

Recycling, here, refers to the process of reusing waste automobile parts for blank production through remanufacturing, recycling and other means, which can effectively reduce the carbon emissions in the production and processing stages. During recycling, some materials of the parts are treated and recycled in the production stage [26,27], and others are returned to the processing stage for material reuse. Hence, the carbon emissions from the recycling of the parts after the lightweight design can be expressed as:

$$\begin{cases} C_r = -\eta_1 \Delta \mathrm{m}_{production} f_m - \eta_2 \Delta \mathrm{m}_{process} f_m \\ \Delta \mathrm{m}_{production} + \Delta \mathrm{m}_{process} = \eta_m \Delta \mathrm{m} \\ \eta_1 + \eta_2 = 1 \end{cases} \tag{7}$$

where C_r is the carbon emissions in the recycling stage of the parts after the lightweight design; $\Delta \mathrm{m}_{production}$ is the mass of the parts reused in the production process; $\Delta \mathrm{m}_{proces\sin g}$ is the mass of the parts reused in the processing stage; η_1 is the utilization rate of the hub material used for reproduction; and η_2 is the utilization rate of the hub material used for reprocessing.

Therefore, the comprehensive carbon emission benefits yielded by the lightweight design of the parts consist of the carbon emissions from the four parts mentioned above, which can be expressed as:

$$\begin{aligned} C_{LD} &= C_{\Delta m} + C_{\Delta p} + C_l + C_r \\ &= \Delta m \times f_m - \sum_{i=1}^{i_n}\sum_{j=1}^{j_n} \Delta M_i \times f_m^j - \sum_{i=1}^{i_n}\sum_{k=1}^{k_n} \Delta E_i \times f_e^k - \sum_{i=1}^{i_n}\sum_{l=1}^{l_n} \Delta W_i \times f_w^l \\ &+ l\eta_w \Delta m - \eta_1 \Delta \mathrm{m}_{production} f_m - \eta_2 \Delta \mathrm{m}_{process} f_m \end{aligned} \tag{8}$$

where C_{LD} is the comprehensive carbon emission benefits of the parts after the lightweight design.

3. Case Study

3.1. Background

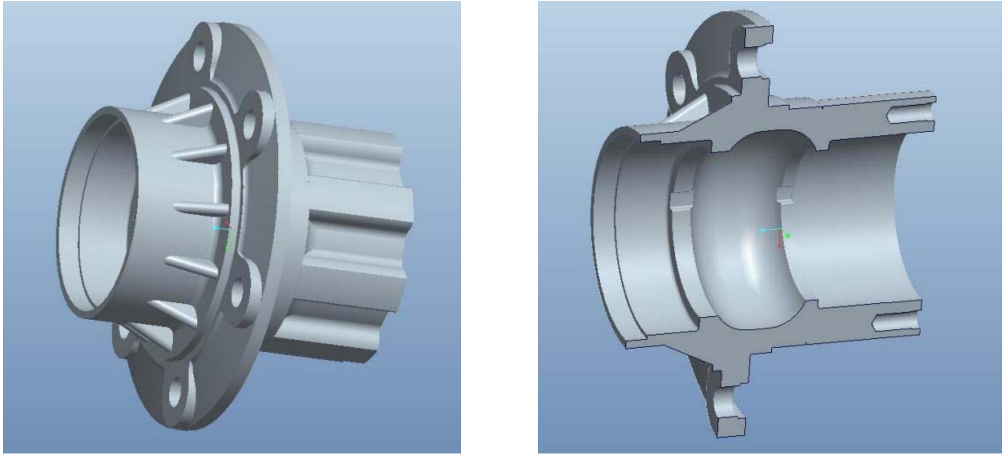
Wheel hubs are one of the important components of a car [28]. As of the first half of 2022, the number of motor vehicles in China has reached 406 million, and each automobile requires several wheels. In 2022, the domestic demand for passenger vehicles in China has reached 21.1 million, an annual increase of 4.4%, and the predicted value at the beginning of the year scored an annual increase of 3%. The large number of annual sales of automobiles have induced a great demand for wheel hubs [29,30]. Experience indicates that for every 1 kg mass reduction of the rotating parts, such as automobile wheel hubs, the mass of the other non-rotating parts will be cut by 1.2–1.5 kg per year. Clearly, the mass reduction of wheel hubs is essential for the application of the lightweight design to automobiles. To date, the lightweight design of wheel hubs has become one of the key technologies for wheel hubs and even automobile manufacturers aiming to improve their core competitiveness.

Therefore, the proposed lightweight brake hub can reduce the carbon emissions produced by brake hub manufacturers and operating vehicles.

3.2. Finite Element Analysis of the Wheel Hub

1. Building a 3D model and performing the meshing

The lightweight design takes the ZS061750-152101 wheel hub designed and manufactured by Anhui Axle Co., Ltd. as the prototype. The wheel hub has a load of 6T and is extensively used. Its 3D model, established by 3D modeling software, is shown in Figure 3.



(**a**) Global view (**b**) Half sectional view

Figure 3. 3D model of the ZS061750-152101 wheel hub.

To reduce the number of unnecessary calculations, the 3D model of the wheel hub is simplified by removing the rounded corners, chamfers, surfaces and irregular entities without violating the actual requirements of ANSYS Workbench for finite element analysis. The simplified 3D model imported into ANSYS is presented in Figure 4.

After the model is imported into the ANSYS software, the meshing is conducted. Concretely, through the Sizing function in the Mesh program, fine meshing is performed on the part where the stress is concentrated, i.e., on the installation rabbet, while sparse meshing is performed on the other parts that are slightly stressed or not stressed. The results of the meshing are exhibited in Figure 5. A total of 145,211 3D tetrahedral solid units and 244,181 nodes are divided.

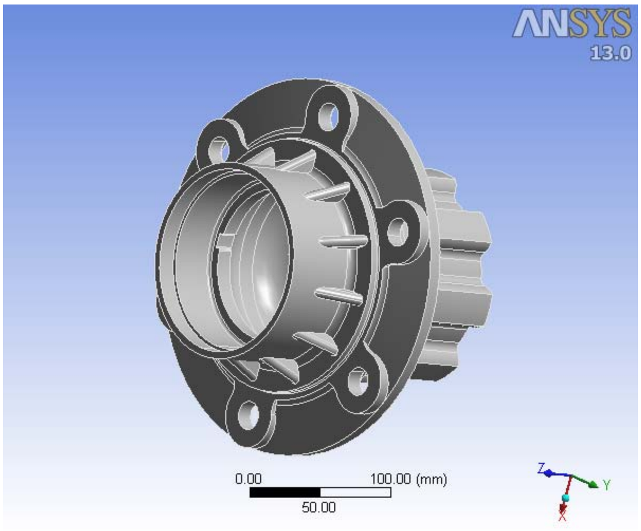
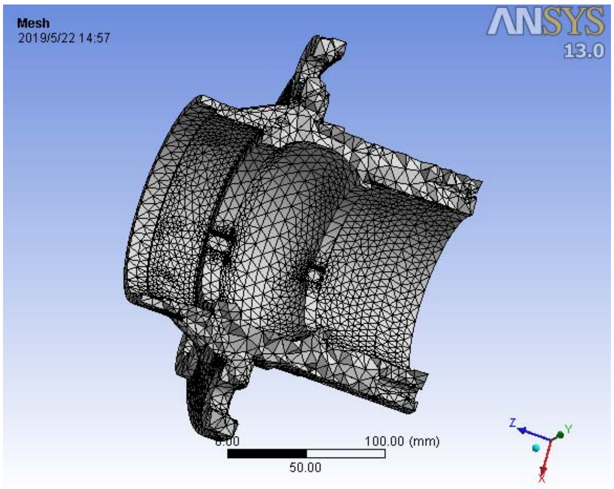
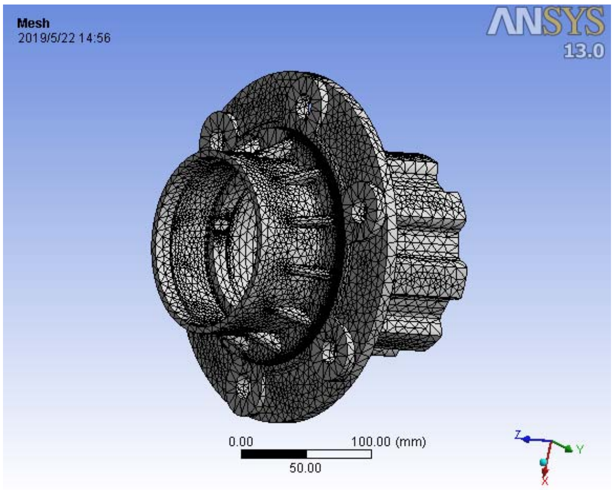


Figure 4. Simplified 3D model of the wheel hub.



(**a**) Internal mesh units



(**b**) Whole mesh

Figure 5. Meshing model of the wheel hub.

2. Adding the material properties

The wheel hub is formed of ductile iron QT500-10, whose properties are listed in Table 1. In this step, these material parameters are added, correspondingly, to the ANSYS software in turn.

Table 1. Mechanical parameters of ductile iron QT500-10.

Symbol	Property	Parameter
E	Elastic modulus (MPa)	1.7×10^5
v	Poisson's ratio	0.29
S_{Yt}	Yield strength (Pa)	3.6×10^8
S_{Ut}	Tensile strength (Pa)	5×10^8
ρ	Density (kg/m^3)	7100

3. Applying the loads

The research object in this paper is the 6T wheel hub. Its maximum load is 6 tons under normal working conditions, and the pressure on a single hub is 30,000N and is distributed along the lower semicircular axis of the wheel hub. Considering that the impact coefficient is 1.67, the rated load of the unilateral hub is 50,000 N. During loading, the pressure load increases linearly to 50,000 N within 1 s and maintains this value for 1–2 s. The tool of ANSYS that we used was a static structural tool. The installation rabbet, i.e., the flange, is the position where the stress is concentrated.

4. Applying the constraints

During working conditions, the hub is subject to 3 degrees of freedom in the translation direction and 2 degrees of freedom in the rotation direction. However, the degree of freedom with the central axis of the hub as the rotation direction is not constrained, and the constraint positions are located at the bearing installation points. Thus, the constraints are set as fully fixed supports (Figure 6).

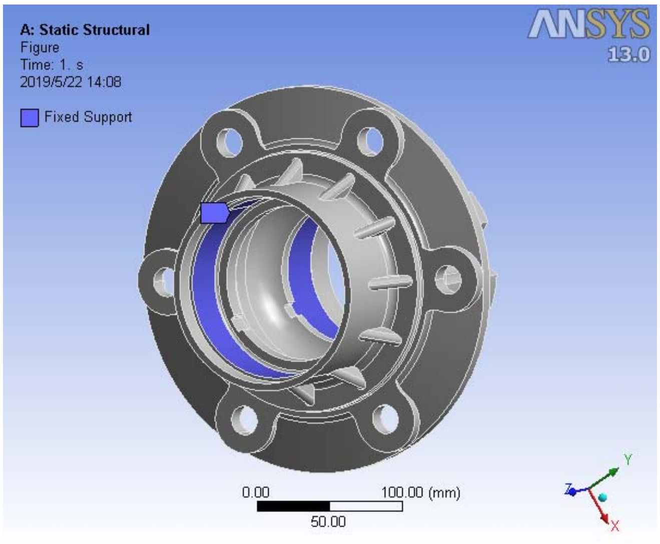
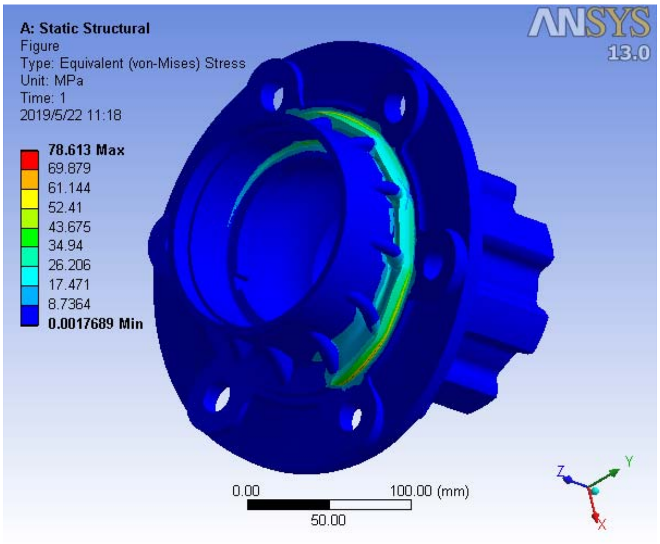


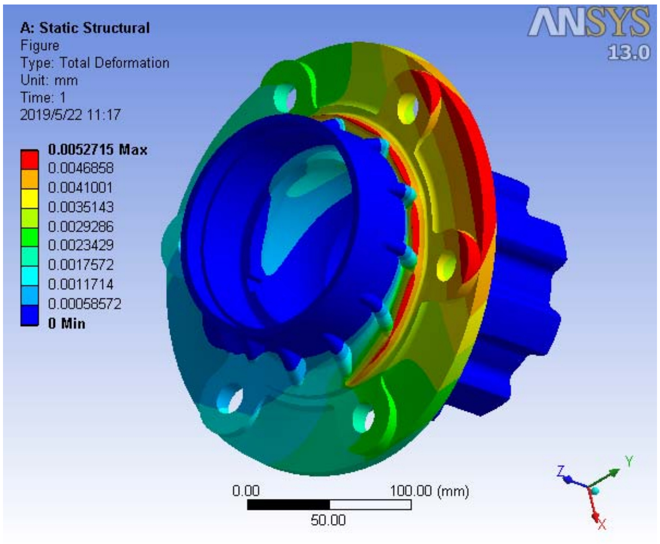
Figure 6. Positions of the constraints applied to the wheel hub.

5. Finite element analysis and results

After running the simulation program, the calculation results are obtained. The contours of the stress, deformation (i.e., displacement) and safety factor of the wheel hub are displayed in Figure 7.



(**a**) Contour of the stress



(**b**) Contour of the displacement

Figure 7. Finite element analysis results.

As can be observed from Figure 7a, the stress is relatively concentrated in the hub installation rabbet, which is in line with the predicted stress and strain positions in practice. In addition, the maximum stress value is 78.613 MPa, which is much lower than its yield limit, i.e., 360 MPa. According to Figure 7b, the maximum deformation is 0.0052715 mm, which is far lower than the specified value, 1 mm. The safety factor is 7.9503, which is greater than the required range, 2–2.5.

6. Fatigue Life Analysis

The S–N curve can be used to describe the relationship between the fatigue strength and service life of the parts.

Its mathematical expression is:

$$NS^{m} = C \tag{9}$$

where N is the life at the time of failure, as well as the number of cycles, and C is a constant.

The wheel hub of an automobile is subjected to unstable variable stress in the period of work, and the theoretical basis for calculating its fatigue strength is the cumulative fatigue damage hypothesis (namely, Miner's law). The mathematical expression is:

$$\sum_{i=1}^{z} \frac{n_i}{N_i} = 1 \tag{10}$$

where n_i is the number of stress cycles at the i-th grade, and N_i is the fatigue life at the i-th grade.

Based on this hypothesis, the engineers and researchers performed numerous experiments and arrived at Equation (11):

$$\sum_{i=1}^{z} \frac{n_i}{N_i} = 0.7 \tag{11}$$

In the Statics module, the number of life cycles of the wheel hub and the fatigue factor for the safe use of the structure are added to the Fatigue Toolbar. Since the fatigue of the wheel hub is defined as high-cycle fatigue, the number of its life cycles is set to be over 10^6. The specific formula of the fatigue notch factor $\mathrm{K_f}$ is shown in Equation (12). The value of $\mathrm{K_f}$ is calculated to be 0.35, and the value of the fatigue strength factor is 1:

$$\mathrm{K_f} = \frac{\sigma_{\max}}{\sigma_{-1}} \tag{12}$$

where $\mathrm{K_f}$ is the fatigue notch factor; $\sigma_{\max}$ is the maximum local elastic stress; and σ_{-1} is the fatigue limit value.

The service life of the wheel hub is calculated using the Fatigue module in the ANSYS Workbench software, and the fatigue properties are added to the material for the analysis. The load spectrum used for the fatigue life analysis of the wheel hub is consistent with the load added in the mechanical analysis. During loading, the pressure load increases linearly to 50,000 N within 1 s and maintains this value for 1–2 s.

For the wheel hub cast with ductile iron, its number of life cycles N should exceed 10^6. According to this standard, the fatigue notch factor is calculated to be 0.35. Then, the life, safety factor and fatigue sensitivity in the solution are solved to obtain the result of the life analysis (Figure 8).

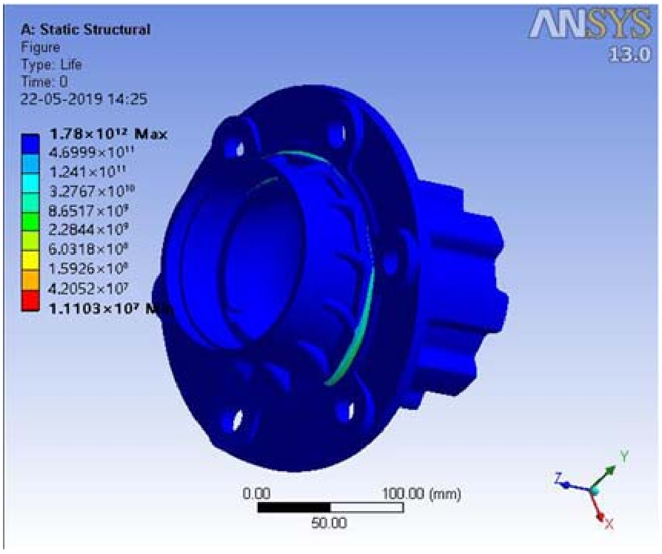


Figure 8. Analysis on the number of life cycles.

From the perspective of the service life, the number of cycles for the safe use of the wheel hub is 1.1103×10^7 (Figure 8), which is much larger than the set number, 1×10^6. This indicates that the service life of the wheel hub meets the requirements.

The above analysis proves that the design of the wheel hub is reasonable and leaves sufficient room for lightweight improvement. For this purpose, further lightweight design strategies can be applied to the wheel hub to render it more economical and efficient.

3.3. Lightweight Design

(1) Determination of the lightweight positions

According to the above analysis, the maximum displacement of the wheel hub is 0.0052715 mm, far smaller than the specified value of 1 mm. The stress is concentrated in the installation rabbet (i.e., the flange), with a maximum value of 78.613 MPa, far smaller than the yield strength (360 MPa) of the wheel hub material, QT500-10. The minimum safety factor is 7.9503, much larger than the required minimum safety factor of 2.0–2.5. The minimum number of life cycles is 1.1103×10^7, much greater than the set number of life cycles of 10^6. The fatigue factor for safe use is 1.2327, which is greater than 1. All these data suggest that the wheel hub has considerable potential for lightweight improvement, which can be realized at such safe positions as the ribs, large cylindrical structure and bosses.

(2) Lightweight design scheme

In the lightweight design, the strength, stiffness and fatigue life of the wheel hub are selected as the constraints. After the lightweight design is applied, the maximum deformation of the wheel hub should be less than 1 mm; the maximum stress should be lower than the yield limit of the raw material (360 MPa); the number of life cycles should exceed the predicted value; and the fatigue factor for safe use should be greater than 1. Only when all these requirements are met can the safety and reliability of a lightweight wheel hub during its use be guaranteed.

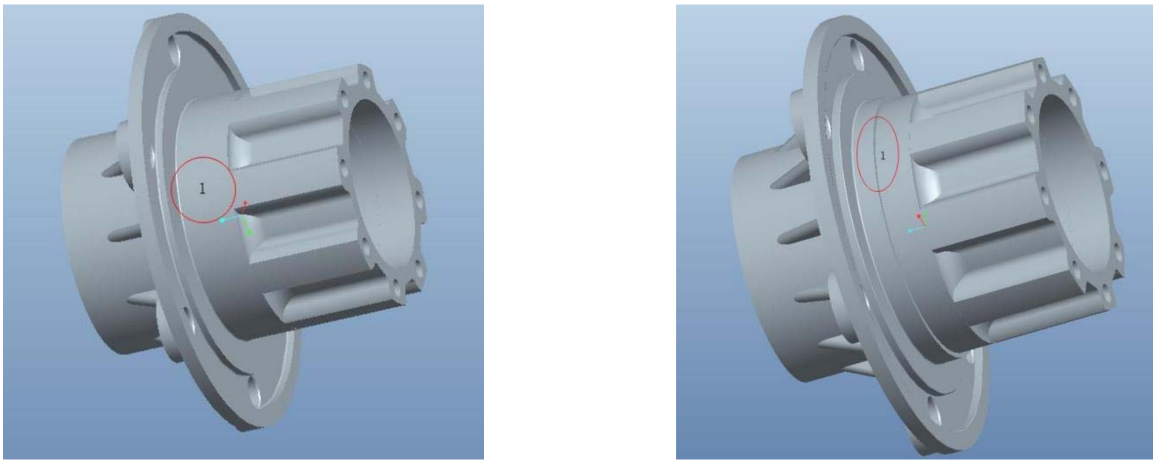
From the finite element analysis results, the ribs, large cylindrical structure and bosses are safe positions that can be selected for lightweight design. The mass can be reduced by adding holes, reducing the auxiliary structure, adding grooves or thinning. The designed lightweight scheme is described as follows: the structure at the axle neck is removed (in Figure 9, position 1, adding grooves); the width of the reinforcing rib is reduced from 33 mm to 30 mm (in Figure 9, position 2, thinning), and its number is decreased from 12 to 10 (reducing auxiliary structure); and a groove with a depth of 2 mm is dug into the installation rabbet (in Figure 9, position 3, adding grooves). The details of the lightweight design scheme modifications are presented in Figure 9.

As exhibited in Figure 9, the lightweight design also leads to some changes in the process: at Position 1, lathe cutting to a depth of 60 mm and a width of 5 mm is required; at Position 2, the time required to create the sand mold in the casting process is shortened; and at Position 3, the milling cutter must be used to dig one more groove that is 2 mm deep and 50 mm wide.

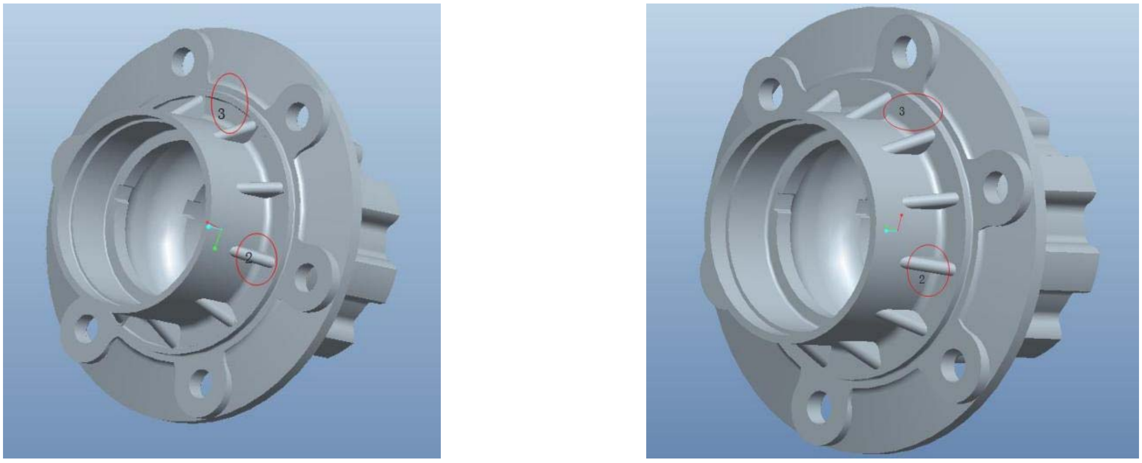
3.4. Carbon Emission Results

(1) Comparative analysis of the mechanical properties of the wheel hub before and after the lightweight design

With the aid of the ANSYS Workbench software, the wheel hub after the lightweight design is analyzed in accordance with the procedure described in Section 3.2. The meshing results of the wheel hub after the lightweight design are displayed in Figure 10. A total of 226,716 nodes and 136,773 solid units are divided.



(**a**) After the lightweight design (Position 1) (**b**) Before the lightweight design (Position 1)



(**c**) After the lightweight design (Positions 2 and 3) (**d**) Before the lightweight design (Positions 2 and 3)

Figure 9. Lightweight design scheme.

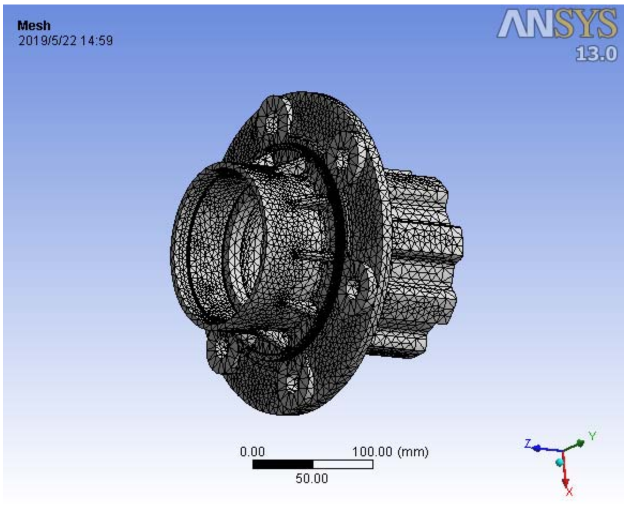
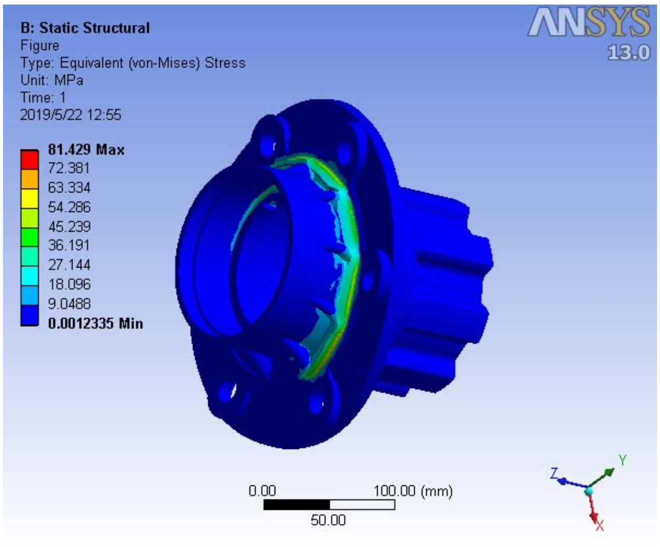
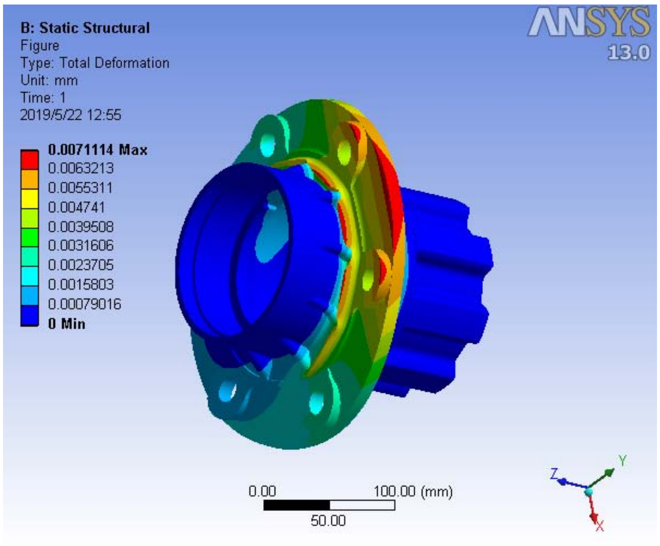


Figure 10. Meshing of the wheel hub after the lightweight design.

The contours of the stress and displacement of the wheel hub based on the simulation analysis and calculations are depicted in Figure 11.



(**a**) Contour of the stress after the lightweight design



(**b**) Contour of the displacement after the lightweight design

Figure 11. Simulation analysis results of the wheel hub after the lightweight design.

The number of life cycles of the wheel hub after the lightweight design yielded from the life fatigue analysis is displayed in Figure 12.

As illustrated in Figure 11, after the lightweight design, the maximum stress value of the wheel hub is increased to 81.429 MPa, but it remains lower than the yield limit value (360 MPa) of its raw material. The deformation at the installation rabbet increases slightly to 0.0071114 mm (compared with Figures 5 and 6), which is still less than 1 mm, suggesting that the deformation remains within the required range. The safety factor is 7.6754, exceeding the required minimum value of 2–2.5, that is, it is up to standard. As indicated in Figure 12, the minimum number of life cycles for safe use is 8.2088×10^6, which exceeds the set number of 1×10^6; thus, it satisfies the requirements. In conclusion, the wheel hub succeeds in realizing the lightweight quality while guaranteeing its required working performance.

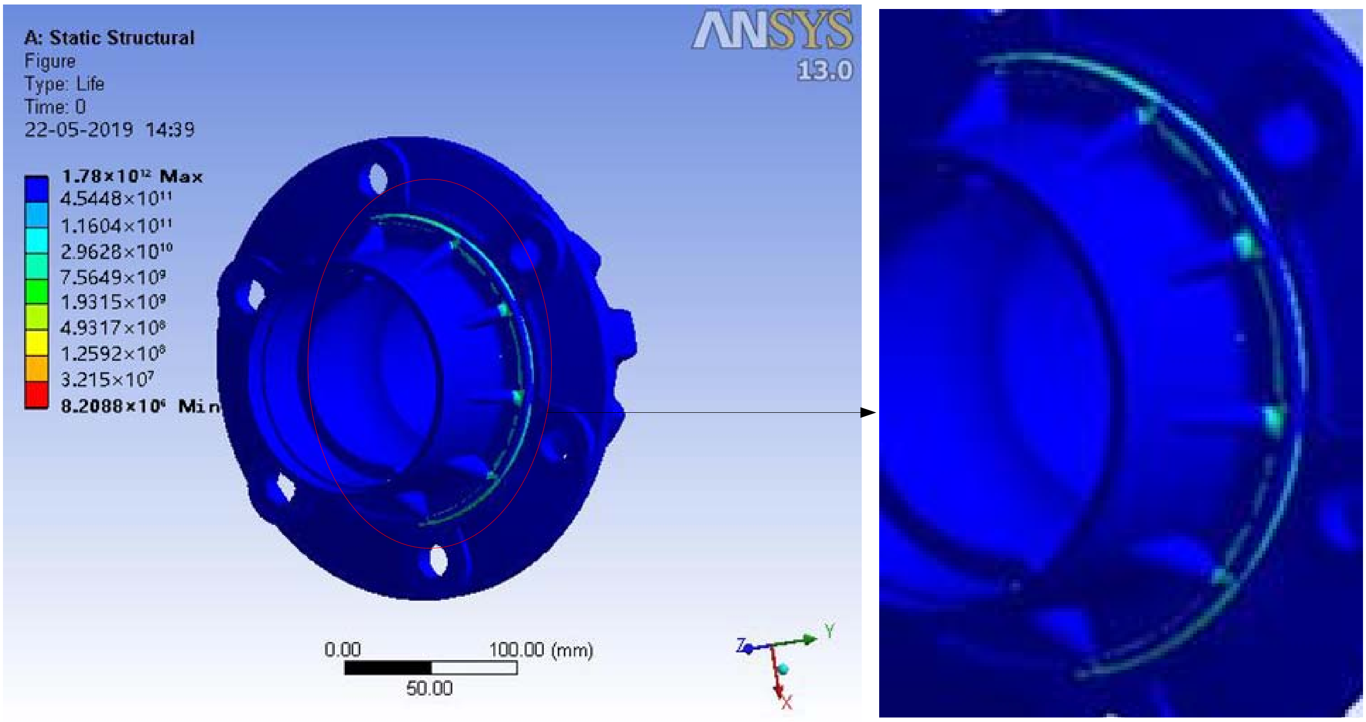


Figure 12. Number of life cycles of the wheel hub after the lightweight design (including a partial enlarged view).

The simulation results of the mechanical properties of the wheel hub before and after the lightweight design are compared in Table 2.

Table 2. Comparison of the mechanical properties of the wheel hub before and after the lightweight design.

No.	Parameter	Before the Lightweight Design	After the Lightweight Design	Value Change	Proportion of Change (%)
1	Stress (MPa)	78.613	81.429	2.816	+3.58
2	Displacement (mm)	0.0052715	0.0071114	0.0018399	+34.9
3	Safety factor	7.9503	7.6754	0.2749	−3.46
4	Fatigue life	1.1103×10^7	8.2088×10^6	2.823×10^6	−26
5	Gross mass (kg)	11.895	10.495	1.4	−11.77

(2) Analysis of the emission reduction benefits after the lightweight design

The lightweight design inevitably increases processes such as the turning and milling. With respect to the turning process, the processing equipment is a cylindrical lathe, CA6140. The parameters commonly used by this company include the following: in rough turning, the spindle speed of 150 r/min, the feed rate of 0.4 mm/r and the cutting depth of 3 mm; in semi-rough turning, the spindle speed of 200 r/min, the feed rate of 0.3 mm/r and the cutting depth of 1.5 mm; and in finish turning, the spindle speed of 450 r/min, the feed rate of 0.2 mm/r and the cutting depth of 0.5 mm. When the lathe is not loaded, its average power is 5350 W, and the non-load duration is 10 s. At the time of processing, its average power is 6450 W, and the processing lasts for 180 s in total. As for the milling process, the equipment used is a SINMERIK808D CNC milling machine, and the rod-shaped milling cutter is used for the plane milling. The specific parameters of the milling machine include: the feed rate of 1 mm/min, the rotational speed of 1500 r/min, the processing time of 120 s, the idle duration of 10 s, the idle power of 150 W and the average power during processing of 1750 W.

The carbon emissions added in the turning and milling processes originate from the consumed electric energy, cutting tool and cutting fluid. In the light of Equations (2)–(8), these emissions can be calculated according to Equation (13):

$$\begin{cases} \Delta C_m = \Delta m_1 f_m^1 + \Delta m_2 f_m^2 + \Delta m_3 f_m^3 + \Delta m_4 f_m^4 \\ \Delta C_e = E_1 f_e^1 + E_2 f_e^2 \end{cases} \tag{13}$$

where Δm_t is the mass of the cutting tool used in the added processes after the lightweight design, kg; f_t is the carbon emission factor of the cutting tool, kg/kg; Δm_l is the mass of the cutting fluid used in the added processes after the lightweight design, kg; and f_l is the carbon emission factor of the cutting fluid, kg/L.

The casting process before and after the lightweight design barely changes, except for the increased amount of silica sand. According to Equations (2)–(8), the carbon emission caused by the increased amount of silica sand can be determined using Equation (14):

$$C_{si} = \frac{\Delta m}{\rho} \rho_{si} f_m^{si} \tag{14}$$

where ρ is the density of the hub material; ρ_{si} is the density of the silica sand, kg/m^3; and f_{si} is the carbon emission factor of the silica sand, kg/kg.

Survey results of Anhui Axle Co., Ltd. demonstrate that about 70% of the parts are recycled in the forging and casting stage after they are scrapped, and approximately 30% are recycled in the processing stage. With reference to the literature [31,32], the meanings and values of the symbols in Equations (1)–(14) can be determined (Table 3).

Table 3. Meanings and values of the symbols [33–35].

No.	Meaning	Symbol	Value	Unit
1	Mass variation arising from the lightweight design	Δm	1.4	kg
2	Carbon emission factor of the hub material	f_m	2.69	kg/kg
3	Kilometers traveled	l	7×10^5	Km
4	Emission coefficient per kilometer	η_w	5×10^{-5}	Km^{-1}
5	Utilization rate of the hub material for reproduction	η_1	0.7	/
6	Utilization rate of the hub material for reprocessing	η_2	0.3	/
7	Utilization rate of the parts	η_m	0.6	/
8	Mass of the parts reused in the production process	$\Delta \mathrm{m}_{production}$	0.588	kg
9	Mass of the parts reused in the processing stage	$\Delta \mathrm{m}_{process}$	0.252	kg
10	Mass of the cutting tool used in the added turning process	Δm_1	2.7×10^{-4}	kg
11	Mass of the cutting fluid used in the added turning process	Δm_2	3.8×10^{-3}	L
12	Mass of the cutting tool used in the added milling process	Δm_3	2.2×10^{-4}	kg
13	Mass of the cutting fluid used in the added milling process	Δm_4	4.2×10^{-3}	kg
14	Energy consumed in the added turning process	E_1	0.34	Kwh
15	Energy consumed in the added milling process	E_2	0.059	Kwh
16	Grid emission factor of turning	f_e^1	0.499	kg/Kwh
17	Grid emission factor of milling	f_e^2	0.499	kg/Kwh
18	Carbon emission factor of the cutting tool in turning	f_m^1	29.6	kg/kg
19	Carbon emission factor of the cutting fluid in turning	f_m^2	2.85	kg/L
20	Carbon emission factor of the cutting tool in milling	f_m^3	29.9	kg/kg
21	Carbon emission factor of the cutting fluid in milling	f_m^4	2.95	kg/L
22	Carbon emission factor of the silica sand	f_m^{si}	7×10^{-3}	kg/kg
23	Density of the hub material	ρ	7.85	kg/m^3
24	Density of the silica sand	ρ_{si}	2.65	kg/m^3

By substituting the values in Table 3 into Equations (1)–(14), the comprehensive carbon emission benefit of the wheel hub after the application of the lightweight design can be determined, as shown in Equation (15). Meanwhile, the carbon emission benefits of each part caused by the lightweight design can be obtained, as shown in Table 4.

$$
\begin{aligned}
&C_{LD} = \Delta m \times f_m - \sum_{i=1}^{i_n} \sum_{j=1}^{j_n} \Delta M_i \times f_m^j - \sum_{i=1}^{i_n} \sum_{k=1}^{k_n} \Delta E_i \times f_e^k - \sum_{i=1}^{i_n} \sum_{l=1}^{l_n} \Delta W_i \times f_w^l \\
&+ l\eta_w \Delta m - \eta_1 \Delta \mathrm{m}_{production} f_m - \eta_2 \Delta \mathrm{m}_{process} f_m \\
&= 1.4 \times 2.69 - 0.34 \times 0.499 - 0.059 \times 0.499 - 2.7 \times 10^{-4} \times 29.6 - 3.8 \times 10^{-3} \times 2.85 - 2.2 \times 10^{-4} \times 29.9 \\
&- 4.2 \times 10^{-3} \times 2.95 + \frac{1.4}{7.85} \times 2.65 \times 7 \times 10^{-3} + 7 \times 10^5 \times 5 \times 10^{-5} \times 1.4 - 0.588 \times 0.7 \times 2.69 - 0.252 \times 0.3 \times 2.69 \\
&= 51.22(\mathrm{kg})
\end{aligned}
\tag{15}
$$

Table 4. Carbon emission benefits of each link caused by the lightweight design.

Link	Carbon Emission from Mass Reduction after the Lightweight Design	Carbon Emission from Changes in Manufacturing Processes after the Lightweight Design	Carbon Emission from Use of the Parts after the Lightweight Design	Carbon Emission from Recycling of the Parts after the Lightweight Design	Comprehensive Carbon Emission Benefits of the Wheel Hub after the Application of the Lightweight Design
Carbon emission benefit/kg	$C_{\Delta m}$	$C_{\Delta p}$	C_l	C_r	$C_{LD} = C_{\Delta m} + C_{\Delta p} + C_l + C_r$
	3.77	−0.24	49	−1.31	51.22

The comprehensive carbon emission benefits of the wheel hub after the application of the lightweight design amount to 51.22 kg.

We performed more experiments and simulations to demonstrate the efficiency, novelty and advancement of the suggested method. The application of this method to the automobile parts achieved good results. In this paper, the use of lightweight vehicles, the manufacturing enterprise and carbon emission benefits of each link caused by the lightweight design were considered and calculated, as shown in Table 5.

Table 5. The application of this method to the automobile parts.

No.	Part Name	Lightweight Design Scheme	Reduced Weight		Simulation Parameters Proportion of Change				Carbon Emission Benefit (kg)		Carbon Reduction Process Considered	Reference
			Mass (kg)	Proportion of Change (%)	Stress (MPa)	Displacement (mm)	Safety Factor	Fatigue Life	A Truck	An Enterprise		
1	Axle hub	Removed the step	−4.741	−5.537	+39.68	+0.0129	−1.059	–		–	–	[28]
2	Special Axle Hub	Widened the wheel hub and reduced thickness and stiffener number	−71.25	−7.52	+48.88	+0.0117	−3.22	–	4.99×10^5	–	Use of lightweight vehicles	[36]
3	Brake Hub	Increased the outer circle and the number of bolt holes	−4.21	−17.4	−6.187	−0.00161	−0.4275	–	2.921×10^3	8.76×10^8	Use of lightweight vehicles and manufacturing enterprise	Anhui Axle Co., Ltd. and [37]
4	Wheel hub	Added holes, grooves	−1.4	−11.77	+2.816	+0.0018	−0.2749	-2.823×10^6	1.024×10^3	2.56×10^7	Use of lightweight vehicles, manufacturing enterprise and carbon emission benefits of each link caused by lightweight design	This paper

3.5. Discussion and Management Implications

In addition to carbon emissions caused by lightweight parts, this study also has the following advantages compared with the previous research literature [38]. The lightweight design method for carbon emissions, a calculation method for the carbon emissions of automotive parts after lightweight design application, was presented. After the lightweight design, the changed carbon emissions were calculated, including the quality, process, use and recovery, the low carbon benefits of the lightweight solutions were comprehensively evaluated. This study provides theoretical support for the evaluation of the carbon emissions caused by the lightweight design of industrial automotive production processes. It can improve the lightweight design method for automotive parts and enhance the carbon emission reductions of the industrial automotive production process, which serves as the basis and foundation of production management for the sustainable development of automobile enterprises. Last but not least, an effective method that considers the mass change, process, use and recovery of parts and a case used to evaluate the carbon emissions caused by the lightweight design of the industrial automotive production process were obtained based on the carbon impact factor, and the low carbon benefits of the lightweight solutions were comprehensively evaluated. The results provide a convenient theoretical and methodological support for improving the comprehensive level of low-carbon, lightweight design, as well as green and clean manufacturing, and promoting the sustainability of the industrial automotive production process.

The proposed lightweight wheel hubs can reduce the carbon emissions of brake hub manufacturers and operating vehicles. With reference to the aforementioned research results on the lightweight design of the brake hub, the low carbon benefits of a truck with this wheel hub over its entire life cycle can be estimated. Let us suppose that the truck has a total number of 20 wheel hubs with a weight loss of 1.4 Kg per hub, and that the comprehensive carbon emission benefit is 51.22 kg per hub. Therefore, the total weight of the vehicle is reduced by 28 Kg, with mandatory mileage scrapping 7×10^5 km. The truck has a total carbon emissions score of $Q_w = 1024.4$ Kg, and the emission reduction effect is relatively obvious. Considering Anhui Axle Co., Ltd. (a medium-sized axle manufacturing and processing enterprise) as an example, with an annual output of 500,000 sets of wheel hubs, n =500,000, it can be calculated that the lightweight braking hub will reduce the carbon emissions by $Q_m = 2.56 \times 10^7$ Kg for Anhui Axle Co., Ltd. If all the enterprises of the same type as Anhui axle Co., Ltd. were to use the lightweight hub, the emission reduction benefits to the whole of society would make a great contribution.

Based on the above research and conclusions, the following three implications can be yielded:

First, as the global response to climate change continues to grow, carbon peak and carbon neutrality have become a global focus [39,40], which poses both great challenges and opportunities for the automotive industry [41,42]. Against such a background, the automotive industry can reduce carbon emissions by starting with the lightweight component design.

Secondly, lightweight solutions usually add supplementary processes. However, the carbon emissions resulting from the new process (Equations (2)–(8)) are less than those resulting from weight reduction (Equation (1)), and this part of the carbon emissions can be further reduced by the further overall optimization of the production process and improvement of the production equipment.

Thirdly, the carbon emission reduction benefits of the lightweight design are considerable, but sometimes the mechanical properties of the parts are forfeited (although they are all within the design limits). The trade-off between the benefit of the lightweight emission reduction and the mechanical properties is worth considering for decision makers.

4. Conclusions

This paper proposed a lightweight design method for the carbon emissions of automobile systems. The main innovations are as follows:

(1) Firstly, the finite element method was adopted to analyze the stress, strain and safety factor of the automobile parts based on their stress, so as to identify the positions where the lightweight design was applicable. Subsequently, a lightweight scheme was

designed accordingly. Next, the finite element method was re-applied to the parts whose weights had been reduced for the purpose of analyzing their stress, strain and safety factor. In this way, the feasibility of the lightweight scheme was verified.

(2) A method for calculating the carbon emissions caused by the lightweight design based on the whole life cycle of the hub was proposed. The method can be adopted to measure the carbon emissions arising from changes in the mass, process and whole life cycle after the application of the lightweight design and then to evaluate the low carbon benefits.

(3) The feasibility of the lightweight design scheme was verified by taking the ZS061750-152101 wheel hub designed and manufactured by Anhui Axle Co., Ltd. as an example for the case analysis. The lightweight design changes three structures of the wheel hub, reducing its weight by 1.4 kg in total. For a single wheel hub, the carbon emissions resulting from the saved material, changed manufacturing processes and application and recycling of the parts are reduced by 51.22 kg in total. That is to say, if the lightweight scheme were to be applied to all the wheels produced by Anhui Axle Co., Ltd. (about 500,000 per year), the carbon emissions from the wheel production, application and recycling processes could be cut by 2.56×10^7 kg, marking a favorable emission reduction effect.

The proposed method serves as a reference for the lightweight design of the spare parts of automobiles and other equipment, and it also provides a new method for calculating the carbon emission changes resulting from the design, use and recycling of the parts after the application of the lightweight design. However, there are still some limitations.

Firstly, in the case analysis, although each component of the parts still satisfies the operating requirements, the lightweight property is achieved at the expense of some of the mechanical properties of the parts.

Secondly, for a total wheel hub carbon emission reduction of 51.22 kg, the greatest loss in the mechanical performance (displacement) reached 34.9%, and the minimum performance loss (safety factor) has reached 3.46%. The relationship between the emission reduction benefits and loss in the mechanical properties has a positive correlation. As the global response to climate change continues to grow, carbon peak and carbon neutrality have become a global focus. China named carbon peak and carbon neutrality as two of the eight major tasks of the central economic work undertaken in 2021 [1]. Against such a background, decision makers will adopt methods that can reduce carbon emissions while the mechanical properties meet the requirements [36]. The quantitative relationship between the loss in the mechanical properties and lightweight quality has not been clarified, and the emission reduction benefits have not been comparatively analyzed with respect to the loss in the mechanical properties. In the follow-up research, efforts will be made to investigate the relationship between the emission reduction benefits and the loss in the mechanical properties in the hope of providing greater convenience for decision makers.

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