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A trade-off optimization model of environment impact and manufacturing cost for machining parts

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Abstract

Motivation: Throughout the life cycle, the environmental impact and manufacturing costs of a part are largely determined at the design stage. Therefore, a part design optimization method considering these two factors is proposed in this paper. At the same time, the comprehensive benefit is taken as the trade-off of these two factors. The reduction of the comprehensive benefit indicates that the optimized part has achieved better environmental and economic performance results.

Methods: Firstly, the model is reconstructed using the dimension-driven method, and the feature information of the new part is extracted. Then, machining process planning is carried out based on the feature information. Secondly, a design optimization model for the comprehensive benefit is established based on the genetic algorithm. The model takes the dimension parameters of the part as the optimization variables and the reduction of the comprehensive benefit as the optimization objective. With the help of the Simulation plug-in for SolidWorks, the static analysis of the optimized model is conducted to determine whether it meets the performance requirements. Finally, the design optimization prototype system oriented to comprehensive benefit is established. The feasibility and effectiveness of the proposed method are verified by taking the intermediate shaft of the belt conveyor reducer-sixth order step shaft as an example.

Results: The case study shows that the optimization result of comprehensive benefit is 1.63%, which verifies the feasibility and effectiveness of the part design optimization method proposed in this paper.

Keywords: Feature information, machining process planning, dimension parameters, comprehensive benefit

INTRODUCTION

The development of the economy and technology has led to increased energy consumption and pollutant emissions, and the environment is deteriorating[1-3]. In addition, due to the constraints of resources and the environment, the era of high costs is also coming, and the sustainable development of the mechanical parts manufacturing industry is facing significant challenges. Therefore, the resource consumption and environmental impact of parts in the manufacturing process are receiving growing attention. Although the cost of a part design only accounts for 10%-15% of the total, it has a decisive impact on the subsequent 80% cost consumption[4], and 75% of the environmental impact is directly or indirectly caused by the design stage[5].

Life cycle assessment (LCA), an environmental performance evaluation tool, is widely used in part design decisions[6]. However, it usually does not involve the economic or social aspects of the part[7]. Designers cannot make the final decision based only on the environmental assessment results. Therefore, it is necessary to combine LCA with other economic analysis tools. The economic analysis tool mostly used in integrating with LCA is called life cycle costing (LCC). Campbell *et al*. proposed a technology and economic evaluation method to reduce shielding gas consumption[8]. The other method calculates environmental costs by integrating LCA and LCC. Georgiadis and Besiou use dynamics ideas to analyze environmental and economic sustainability for waste electrical and electronic equipment (WEEE) closed-loop supply chains with recycling[9]. Santos *et al*. proposed an automatic LCA/LCC analysis within a building information modeling (BIM)-based environment[10]. Hou *et al*. proposed an integrated LCA-LCC model of environmental and economic factors for highway engineering technical schemes[11]. Moreover, further research on improving and optimizing the initial design after getting the integrated evaluation result has not been mentioned.

For this problem, Xiao *et al*. established the energy consumption and cost objectives in the manufacturing and further processing of blanks by optimizing the parameters[12]. Ameli *et al*. proposed an optimization method based on mathematical planning used as a design aid tool that enables a designer to assess the life cycle cost and environmental impact[13]. Deng *et al*. proposed a method for optimizing initial part design to achieve optimal environmental and economic performance results in initial mechanical part design[14]. Based on the theory of social willingness to pay for potential environmental impacts, Shi *et al*. identified the resource consumption, environmental emissions, and costs of mechanical part manufacturing from an economic and ecological perspective[15]. They provided theoretical and data support for energy conservation and mechanical part manufacturing emission reduction. Simões *et al*. used LCA/LCC to evaluate the life cycle environment and economic performance of three different car multimedia solution chassis[16]. Zhang and Meng use a multi-target decision-making method to design the index system, establish the evaluation optimization algorithm model of the green electromechanical part design scheme, and comprehensively evaluate and optimize the green part design scheme from the aspects of the economy[17].

In summary, current research on design optimization often occurs after the design is completed. It fails to utilize the relevant feature information of the solid model fully and requires a significant amount of resources and time to collect environmental impact and cost data. However, with the powerful and comprehensive API interface, SolidWorks allows designers to access part feature information easily through secondary development techniques. In the use of SolidWorks for product design, Hu *et al*. studied the intelligent and automatic design method of hammer mill parts through dynamic link library (DLL) development with the help of SolidWorks secondary development technology[18]. Xue *et al*. proposed the development of computer-aided design software for the shell-and-tube heat exchanger based on SolidWorks parameterized design and SQL data management[19]. Reddy *et al*. proposed a constraint-based

SolidWorks modeling design method that can generate automatic and hierarchical SolidWorks models based on constraint relations among geometric objects[20]. Li and Yin extracted the mates feature information of the top-level parts in the structural feature tree of the CAD model in the SolidWorks platform with the help of SolidWorks API technology[21]. The extracted information is then arranged in a certain order and stored in the database. Based on this, a new design structure matrix generation system is constructed. Yuan *et al*. developed an interactive parametric design system integrating a three-dimensional assembly model and two-dimensional engineering drawing of a static pressure box by using the macro recording function of SolidWorks as a secondary development tool and Visual Basic language, which realized the static pressure box design automation[22].

Based on the above review, this paper proposes a part design optimization method oriented to the comprehensive benefit of environmental impact and manufacturing cost under the SolidWorks environment [Figure 1]. The part feature information is extracted using SolidWorks API functions. Based on the feature information of the part, generative rules are used to realize the machining process planning of the part. Then, by using the process information of the parts, the optimization model oriented to the comprehensive benefit is established, and the comprehensive benefit is improved by optimizing the part design. Finally, based on the SolidWorks software, a design optimization prototype system oriented to the comprehensive benefit is developed to help designers quickly complete part development by considering environmental impact and manufacturing cost comprehensively in the part design stage.

METHODOLOGY

Machining process planning based on part feature information

In this paper, process information is the basis of establishing an optimization model, and process planning is completed based on part feature information. Therefore, this section focuses on the machining process planning based on feature information. The construction of the optimization model will be introduced in Section "Construction of design optimization model for the comprehensive benefit based on genetic algorithm". The model is the basis of feature information extraction, so this section first uses the dimension-driven method to construct the model. Then, feature extraction and expression of the part are carried out. Finally, machining process planning is realized based on feature information.

Model reconstruction based on the dimension-driven method

The dimension-driven method[23] keeps the model structure of the parts unchanged. All the actual dimensions that affect the model structure are defined as dimension variables, and by assigning different dimension values to these dimension variables, a series of parts with the same structure but diverse dimensions can be obtained. Part modeling using the dimension-driven approach must be supported by a model library[24], which is a set of model files drawn by the user and saved in a specified program directory, and the dimensions required to be modified are marked during the construction of the model library.

When the model requires reconstruction, the "DisplayDimension" interface provided by SolidWorks is used to traverse all the dimensions that necessitate modification, that is, editable dimensions, and display them to the user in the form of a dialog box. For objects such as cylinders, the extracted editable dimension information is shown in Table 1.

Then, the user enters a new value for the corresponding editable dimension in the dialog box. For example, change the values of "Diameter @ Sketch1" to 41 and "Length@Boss-Extrude1" to 61. The background reads them, and the editable dimensions of the model are modified using the "Parameter" interface provided by SolidWorks to obtain a model that meets the needs. The C# implementation code of the "Parameter" interface is as follows:

Table 1. The editable dimension information of a cylinder

Dimension name	Value(mm)
Diameter@Sketch1	40
Length@Boss-Extrude1	60

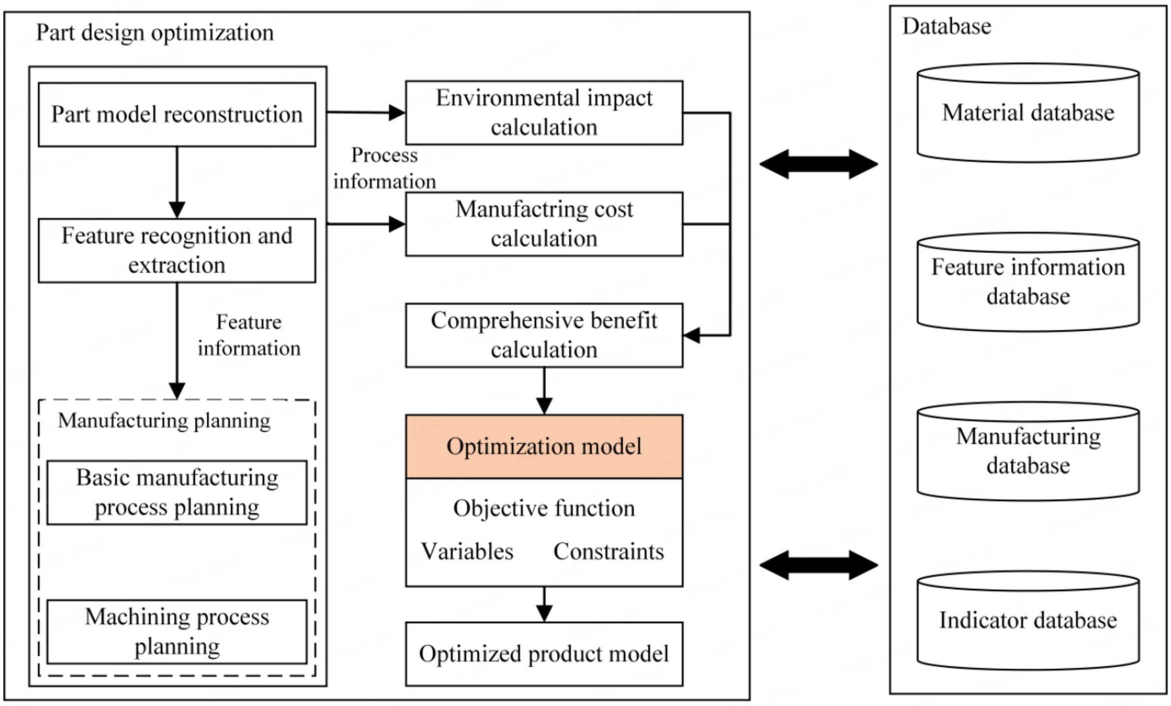


Figure 1. Part design optimization method oriented to the comprehensive benefit.

```
{
……
//Modify the model dimensions.
part.Parameter(Diameter@Sketch1).SystemValue = 0.001 * Convert.ToDouble(41);
part.Parameter(Length@Boss-Extrude1).SystemValue = 0.001 * Convert.ToDouble(61);
//Model reconstruction.
part.EditRebuild;
}
```

The model reconstruction process based on the dimension-driven method is shown in Figure 2.

Part feature identification and expression

Each part contains some features with processing significance, such as holes, slots, faces, chamfers, *etc*. So, obtaining features is particularly important. The geometric feature information of the part is stored in the geometric entity, which can be obtained using the API interface "GetTypeName" provided by SolidWorks. The basic idea of part feature information identification and extraction is as follows. First, the feature traversal is carried out, and the corresponding feature subroutine module is entered according to the feature type and the location of the orientation plane to obtain geometric parameters and other operations. Finally, the related information is saved in the SQL Server 2014 database. The process of feature object recognition is shown in Figure 3. Table 2 presents information on some of the features and their feature dimensions.

Table 2. Part of the feature and feature dimension information

Feature	Dimension type 1	Value 1	Dimension type 2	Value 2	Dimension type 3	Value 3
Cylindrical surface	Diameter	D_1	Length	H_1	-	-
End face	Diameter	D_2	-	-	-	-
Keyway	Width	W_3	Length	H_3	Depth	H_4

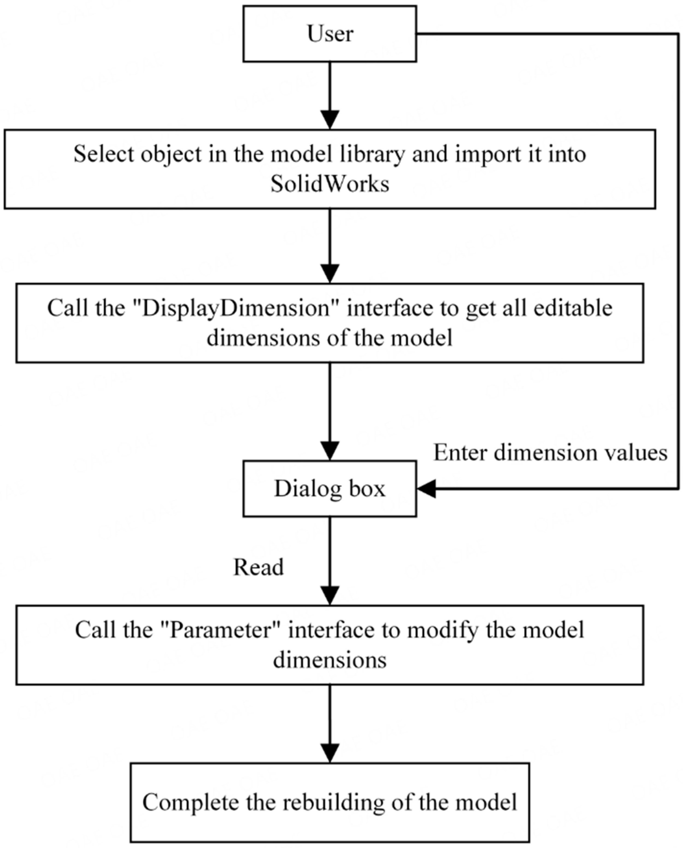


Figure 2. The model reconstruction process based on the dimension-driven method.

All the features of a part constitute the feature set, expressed as:

$$F = \{F_1, F_2, \cdots, F_i, \cdots, F_n\} \tag{1}$$

Where F_i represents the *i-th* feature of the part, and *n* represents the total number of features.

In addition, features contain various types of design information, which requires further orderly expression of information. Therefore, the expression of a single feature design information is established as:

$$F_i = \{T_i, P_i, J_i\} \tag{2}$$

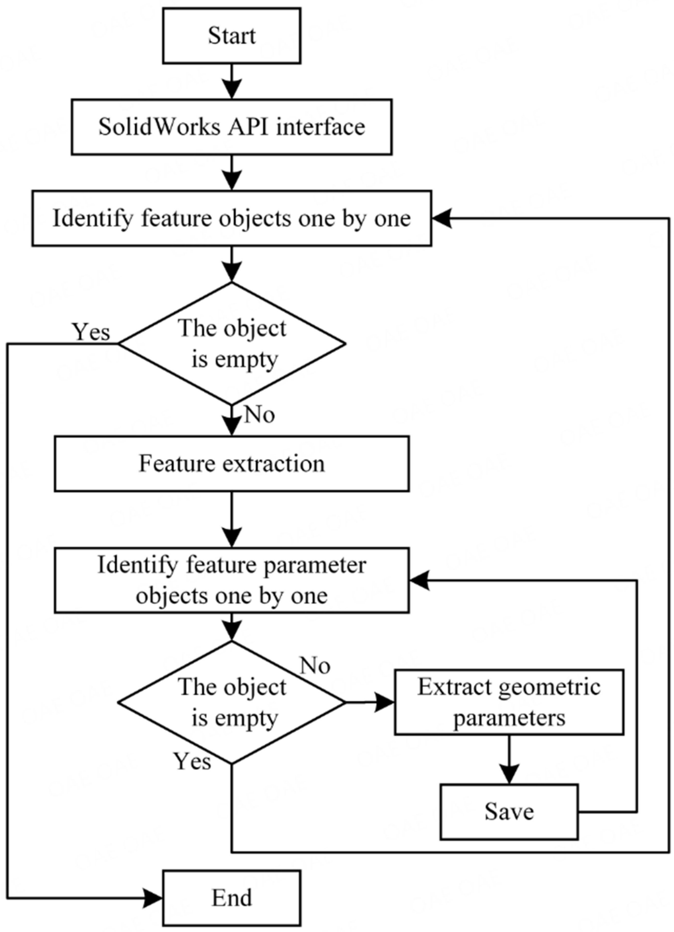


Figure 3. The process of feature object recognition.

Where T_i represents the name of the *i-th* feature, P_i indicates the feature parameter set of the *i-th* feature (including the feature dimension type and its specific value), and J_i denotes the machining accuracy requirement of the *i-th* feature.

Machining process planning based on part feature information

According to the relevant literature research[25-27], the generative rules[28] are used to construct the following table of machining process rules corresponding to different features [Table 3].

The general form of the generative rule is "IF P THEN Q". If the P condition is satisfied, the Q action is taken. For example, if "Feature" = "Cylindrical surface" and "Machining accuracy" = "Rough", then the processing route is "Rough turning". The determination of subsequent processing equipment and cutting tools is based on the process route. For example, if "Process route" = "Rough turning"/"Semi-finishing turning"/"Finishing turning" then "Machining equipment" = "Gold CNC CA6140 horizontal lathe". The machining tools are selected according to the different process routes. The "Grinding wheel" and "High speed steel cylindrical milling cutter" are used for grinding and milling, respectively. YT5 is used for rough turning, and YT15 is employed for semi-finishing and finishing turning.

Table 3. A table of machining process rules corresponding to some features

Feature	Machining accuracy (R_a, μm)	Process route	Machining equipment	Machining tool
Cylindrical surface	Rough (12.5~6.3)	Rough turning	Gold CNC CA6140 horizontal lathe/M1432A Cylindrical grinding machine	YT5/YT15/Grinding wheel
	Semi-finishing (6.3~3.2)	Rough turning, semi-finishing turning		
	Finishing (0.8~0.2)	Rough turning, semi-finishing turning, rough grinding, finishing grinding		
End face	Rough (12.5~6.3)	Rough turning	Gold CNC CA6140 horizontal lathe	YT5/YT15
	Semi-finishing (6.3~3.2)	Rough turning, semi-finishing turning		
	Finishing (1.6~0.8)	Rough turning, semi-finishing turning, finishing turning		
Keyway	Rough (50~12.5)	Rough milling	X5032 vertical milling machine	High speed steel cylindrical milling cutter
	Semi-finishing (6.3~3.2)	Rough milling, semi-finishing milling		
	Finishing (3.2~1.6)	Rough milling, semi-finishing milling, finishing milling		

Construction of design optimization model for the comprehensive benefit based on genetic algorithm

Parts will generate environmental impact and cost throughout the life cycle. Their life cycle generally includes raw material acquisition, manufacturing, transportation, use, and waste recycling stages. Environmental impact and cost at the raw material acquisition and manufacturing stages can be obtained through the feature information of parts. However, they are also related to transport vehicles, transport distance, actual working conditions, local environment, and other factors in the remaining three stages. Therefore, the design optimization model considers only the comprehensive benefit of environmental impact and cost at the raw material acquisition and manufacturing stages.

Genetic algorithm

The optimization model constructed in this paper aims to reduce the comprehensive benefits of the parts, which is a single-objective optimization. At present, common single-objective algorithms include genetic algorithm[29], particle swarm optimization[30], colony algorithm[31], *etc.* All of them can be used as optimization tools in this paper. However, compared with other methods, the genetic algorithm has the following advantages: (1) Powerful global search ability. It can explore the whole search space and has the opportunity to jump out of the local optimal solution to find the global optimal solution or get close to the optimal solution; (2) Powerful adaptability. The genetic algorithm can be adjusted and optimized according to the structure and characteristics of the problem. Setting appropriate parameters and operations can better adapt to the characteristics of the problem and improve the search performance; (3) Powerful parallel performance. The genetic algorithm is inherently parallel. It can achieve multiple individual evolutions through parallel operation, thus speeding up the search process; (4) Powerful interpretability. The running process of the genetic algorithm can be interpreted as the change and evolution of individual adaptability in the population, which exhibits a high degree of interpretability.

Therefore, the genetic algorithm is chosen as the optimization tool of this paper. Figure 4 shows the basic flow of the genetic algorithm. The steps of part design optimization based on the genetic algorithm are as follows:

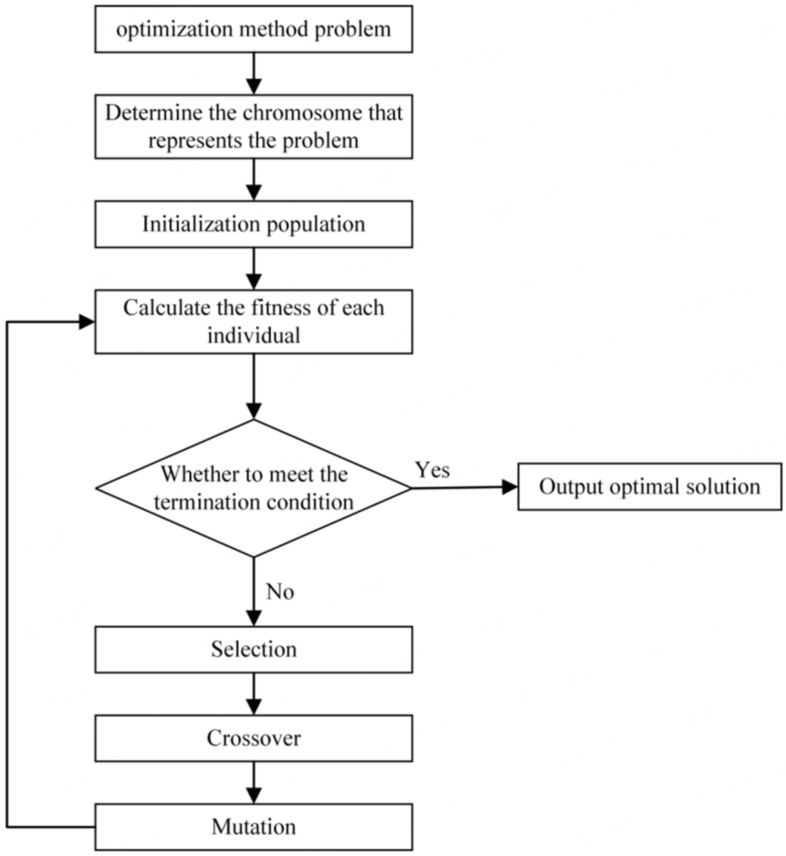


Figure 4. Flow chart of genetic algorithm.

(1) Initialize the population. Randomly generate N individuals to form a population;

(2) Fitness calculation. The fitness calculation formula is the main means of this algorithm to evaluate individual merits. Population fitness is calculated according to the problem. This paper takes the comprehensive benefit of the part as the fitness function;

(3) Selection. The excellent individuals are selected from the current population and used as the parent population to pass on their excellence to the next generation;

(4) Crossover. Crossover operation can generate new individuals, and the new individuals combine the excellent performance of the parent individuals;

(5) Mutation. Randomly select individuals from the population for mutation. Mutation provides new individuals for the population and develops it for diversification. It is the most important part of the genetic algorithm to avoid local optimality;

(6) Repeat the above steps, and the iteration ends when the maximum number of iterations is reached or the optimal solution is output.

Determination of the objective function

Establish an objective function for the comprehensive benefit of environmental impact and manufacturing cost, obtained as:

$$\min F = \lambda_1 EI + \lambda_2 C \tag{3}$$

Where F represents the comprehensive benefit of the part, which is a trade-off between environmental impact and cost. It can be used to measure the quality of a design. The lower the comprehensive benefit, the better the environmental impact and economic performance results of the design. λ_1 indicates the weighting factor of environmental impact. EI means the environmental impact sub-objective function. λ_2 denotes the weighting factor of manufacturing cost. C symbolizes the manufacturing cost sub-objective function.

Environmental impact sub-objective function

The environmental impact of the raw material acquisition stage is mainly determined by the mass of the raw material and its environmental impact indicators, and the environmental impact of the manufacturing stage is mainly determined by the electric energy consumption of the machining process and its environmental impact indicators.

This paper used "Global Warming Potential (GWP)", "Acidification Potential (AP)", "Photochem. Ozone Creation Potential (POCP)", "Eutrophication Potential (EP)", "Ozone Layer Depletion Potential (ODP)", "Abiotic Depletion elements (ADP e)", and "Abiotic Depletion fossil (ADP f)" of the Institute of Environmental Sciences evaluation index system to evaluate environmental impact comprehensively. Since there are many kinds of environmental impacts and the quantification unit is not uniform, it is necessary to give varying weights to achieve weighted analysis according to the degree of harm of various environmental impacts. The weight factors of the environmental impact indicators chosen for this paper are the weight factors of environmental impacts in Sphera GaBi software[32] [Table 4].

(1) Environmental impact EI_r of the raw material acquisition stage.

$$EI_r = \sum_{l=1}^{7} M \cdot f_l \cdot \omega_l \tag{4}$$

Where M represents the mass of the part. f_l indicates the l-th environmental impact indicator of the raw material. ω_l stands for the weight factor of the l-th environmental impact indicator.

(2) Environmental impact at the manufacturing stage.

The manufacturing stage is processing blanks into finished parts, involving various methods. The processes of casting, forging, heat treatment, and cutting are considered in this paper.

Therefore, the environmental impact EI_m of the manufacturing stage can be calculated by:

$$EI_m = \sum_{l=1}^{7} \left(E_z + E_d + E_r + E_c\right) \cdot f_e^l \cdot \omega_l \tag{5}$$

Table 4. Weight factors of each environmental impact indicator

Type of environmental impact indicator	Unit	Normalization	Weighting	Weight ω_l (nondimensional parameter)
GWP	kg CO_2 eq.	2.37E-14	9.3	2.20E-13
AP	kg SO_2 eq.	4.18E-12	6.1	2.55E-11
POCP	kg Ethene eq.	2.72E-11	6.5	1.77E-10
EP	kg Phosphate eq.	6.33E-12	6.6	4.18E-11
ODP	kg R11 eq.	4.41E-09	6.2	2.73E-08
ADP e	kg Sb eq.	2.77E-09	6.4	1.77E-08
ADP f	MJ	2.63E-15	7	1.84E-14

GWP: Global Warming Potential; AP: Acidification Potential; POCP: Photochem. Ozone Creation Potential; EP: Eutrophication Potential; ODP: Ozone Layer Depletion Potential; ADP e: Abiotic Depletion elements; ADP f: Abiotic Depletion fossil.

Where E_z represents the electric energy consumption of the casting process. E_d signifies the electric energy consumption of the forging process. E_r denotes the electric energy consumption of the heat treatment process. E_c stands for the electric energy consumption of the cutting process. f_e^l indicates the *l-th* environmental impact indicator of the electric energy.

The electric energy consumption E_z of the casting process can be calculated by:

$$E_z = \frac{C_b \cdot M \cdot \Delta T_z}{3.6 \cdot 10^6 \cdot \eta_z} \tag{6}$$

Where C_b represents the specific heat capacity of the raw material. ΔT_z indicates the temperature difference in the casting process of raw material. η_z denotes the electric energy conversion rate in the casting process.

The electric energy consumption E_d of the forging process can be calculated by:

$$E_d = \frac{C_b \cdot M \cdot \Delta T_d}{3.6 \cdot 10^6 \cdot \eta_d} + P_d \cdot T_d \tag{7}$$

Where ΔT_d represents the temperature difference in the forging process of raw material. P_d indicates the average power of the forging process in a working cycle. T_d symbolizes the duration of a working cycle of the forging press. η_d signifies the conversion rate of electric energy in the forging process.

According to ref[33], the electric energy consumption E_r of the heat treatment process can be calculated by:

$$E_r = M \cdot N_b \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 \tag{8}$$

Where N_b represents the standard process energy consumption. k_1 denotes the conversion factor of the common heat treatment process. k_2 stands for the common heat treatment process heating mode factor. k_3 indicates the common heat treatment process part mode factor. k_4 symbolizes the common heat treatment process workpiece material factor. k_5 points to the common heat treatment process loading factor.

The electric energy consumption E_c of the cutting process can be calculated by:

$$E_c = \sum_{k=1}^{O} P_k \cdot T_k \tag{9}$$

It is assumed that the part needs to undergo O times of cutting, and P_k is the average power of the equipment used in the *k-th* cutting. T_k is the time taken for the *k-th* cutting. Its estimation formulas are as follows, according to reference[34] (Only the calculation of the machining time of the cutting method involved in Table 2 is listed).

Cylindrical surface turning processing time:

$$T_k = \frac{H_k + y + \Delta}{N_k \cdot f_k} \tag{10}$$

Where H_k is the height of the cylindrical surface, which indicates the processing length of the *k-th* cylindrical surface turning of the part. $y + \Delta$ is the in-cut and over-cut amount, which is found in the cutting concise handbook. N_k represents the workpiece speed of the *k-th* cylindrical surface turning of the part; f_k indicates the feed of the *k-th* cylindrical surface turning.

Cylindrical surface grinding processing time:

$$T_k = \frac{60K \cdot H_k \cdot N_k}{1000 v_k} \tag{11}$$

Where K represents the correction coefficient, generally 1.2-1.5. H_k is the height of the cylindrical surface, which denotes the processing length of the *k-th* cylindrical surface grinding of the part. N_k stands for the spindle speed of the part during the *k-th* cylindrical grinding process. v_k indicates the *k-th* cylindrical grinding feed rate of the part.

End face turning processing time:

$$T_k = \frac{D_k}{2N_k \cdot f_k} \tag{12}$$

Where D_k is the diameter of the end face. N_k represents the rotational speed of the workpiece during the *k-th* end face turning of the part. f_k signifies the feed of the *k-th* end face turning of the part.

Keyway milling processing time:

$$T_k = \frac{L_k + y + \Delta}{v_f^k} \tag{13}$$

Where L_k is the keyway length, which represents the processing length of the *k-th* keyway milling of the part. v_f^k points to the feed per second of the *k-th* keyway milling of the part.

Therefore, the weighted analysis of the overall environmental impact is calculated by:

$$EI = A\left(EI_r + EI_m\right) \tag{14}$$

Where A is a non-dimensional parameter used to adjust the order of magnitude of environmental impact.

Manufacturing cost sub-objective function
In this paper, the manufacturing cost of parts considers the raw material acquisition and manufacturing stages.

(1) The cost C_r of the raw material acquisition stage is mainly determined by the mass and unit price of the raw material, which is calculated by:

$$C_r = M \cdot f_{rc} \tag{15}$$

Where f_{rc} represents the unit price of raw material.

(2) The cost C_m of the manufacturing stage includes the purchase cost of electric energy consumed by the equipment used in each processing process, tool cost, labor cost, and cutting fluid cost. The replacement cycle of the cutting fluid is one to three months, and this paper only considers the machining process of a single part, so the cost of the cutting fluid is not taken into account.

Therefore, the cost of the manufacturing stage is calculated by:

$$C_m = C_e + C_t + C_h \tag{16}$$

Where C_e represents the purchase cost of electric energy consumed by the equipment used in each manufacturing process. C_t indicates the cost of the cutting tools. C_h stands for the labor cost.

The purchase cost C_e of electric energy consumed by the equipment used in each manufacturing process can be calculated by:

$$C_e = \left(E_z + E_d + E_r + E_c\right) \cdot f_{mc} \tag{17}$$

Where f_{mc} represents the unit price of electricity.

The cutting process will cause the consumption of the cutting tools, so the cost C_t of the cutting tools is calculated by:

$$C_t = \sum_{k=1}^{o} \frac{T_k}{TL_k} \cdot f_k \tag{18}$$

Where TL_k and f_k are the tool life and unit price of the corresponding cutting tool at the *k-th* cutting.

The labor cost C_h can be calculated by:

$$C_h = T \cdot f_h \tag{19}$$

Where T represents the time required for the part to complete all machining processes, and f_h indicates the unit price of the worker.

Therefore, the manufacturing cost calculation is expressed as:

$$C = C_r + C_m \tag{20}$$

Based on the above content, the final objective function is obtained as:

$$\begin{aligned}
\min F &= \lambda_1 EI + \lambda_2 C \\
&= \lambda_1 \left(A\left(EI_r + EI_m \right) \right) + \lambda_2 \left(C_r + C_m \right) \\
&= \lambda_1 \left\{ A \sum_{l=1}^{7} \left[M \cdot f_l + \left(\begin{array}{l} \dfrac{C_b \cdot M \cdot \Delta T_z}{3.6 \cdot 10^6 \cdot \eta_z} + \dfrac{C_b \cdot M \cdot \Delta T_d}{3.6 \cdot 10^6 \cdot \eta_d} + P_d \cdot T_d \\ + M \cdot N_b \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 + \sum_{k=1}^{o} P_k \cdot T_k \end{array} \right) \cdot f_e^{\,l} \right] \cdot \omega_l \right\} \\
&\quad + \lambda_2 \left[M \cdot f_{rc} + \left(\begin{array}{l} \dfrac{C_b \cdot M \cdot \Delta T_z}{3.6 \cdot 10^6 \cdot \eta_z} + \dfrac{C_b \cdot M \cdot \Delta T_d}{3.6 \cdot 10^6 \cdot \eta_d} + P_d \cdot T_d \\ + M \cdot N_b \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 + \sum_{k=1}^{o} P_k \cdot T_k \end{array} \right) \cdot f_{mc} + \sum_{k=1}^{o} \frac{T_k}{TL_k} \cdot f_k + T \cdot f_h \right]
\end{aligned} \tag{21}$$

Selection of optimization variables

In Equation (21), the weighting factor λ_1 of environmental impact and the weighting factor λ_2 of manufacturing cost are determined by a certain method, so they are fixed values. A is a non-dimensional parameter used to adjust the order of magnitude of environmental impact, which is a fixed value. When the raw materials of the parts are determined, the corresponding specific heat capacity C_b and the environmental impact indicator f_l are also established. $f_e^{\,l}$ is the environmental impact indicator of electric energy and is also a fixed value. ω_l is the weight factor of the environmental impact indicator, as given in Table 2. In the casting process, the casting temperature difference ΔT_z is determined by the manufacturing requirements, and the electric energy conversion rate η_z is determined by the technical conditions. ΔT_z and η_z can be regarded as fixed values. In the forging process, ΔT_d and η_d can also be fixed values. The average power P_d is determined by the forging process, and the manufacturing requirements determine the forging time T_d. Therefore, P_d and T_d can also be seen as fixed values. When calculating the energy consumption of the heat treatment process, the corresponding parameters (N_b, k_1, k_2, k_3, k_4, k_5) are determined by the specific heat treatment method and can also be considered as fixed values. In this paper, the average power P_k of the equipment is used to calculate the cutting energy consumption so that P_k can be deemed a fixed value. The region determines the unit price f_{rc} of raw materials, the unit price f_{mc} of unit power, the unit price f_k of cutting tools, and the labor salary f_h, so that they can be viewed as fixed values. The tool life TL_k is also a fixed value. Based on these analyses, it is concluded that the comprehensive benefit value is mainly affected by the quality of raw materials and cutting time.

When the material is constant, variations arise in the dimensions of the part and the volume also changes. As the density remains constant, the mass of the part will change as well. The dimensions of the part do not change much before and after optimization. The cutting parameters can be considered fixed, which leads to the conclusion that the part dimensions determine the cutting time. In summary, the comprehensive benefit value is mainly affected by the dimension parameters of the parts. Therefore, the part dimensions are selected as optimization variables, including the diameter parameter D, the length and depth parameter H, and the width parameter W.

Constraints

In the process of optimizing the design of the mechanical part, a range of permissible values for the part dimensions exists, denoted as:

$$D_{\min} \le D \le D_{\max} \tag{22}$$

$$H_{\min} \le H \le H_{\max} \tag{23}$$

$$W_{\min} \le W \le W_{\max} \tag{24}$$

Designing parts ultimately aims to meet the use requirements for the design objectives, so stress is chosen as a measure to verify whether the optimized part can fulfill the use, as determined by:

$$0 < \sigma \le \sigma_{\max} \tag{25}$$

Where σ is the maximum equivalent stress of the optimized part in the working state, and $\sigma_{\max}$ is the allowable stress of the material used.

Construction of design optimization prototype system under the SolidWorks environment

System development and operating environment

A design optimization prototype system based on SolidWorks is developed to improve the efficiency of part design optimization. The system uses C# language to load the API interface of SolidWorks software. It completes the construction of the human-computer interaction interface for a series of operations, including model reconstruction, feature information extraction, and so on.

The system is built and compiled using Visual Studio 2019 on the Windows 10 operating system. Since optimizing the comprehensive benefit of environmental impact and cost of mechanical parts depends on the underlying data, SQL Server 2014 is integrated to build a basic database for data management and calls. The environment configuration for system development can be found in Table 5.

System structure design

The design goal of the prototype system is to provide users with functions such as part model reconstruction, material setting, dimension information extraction, feature identification, machining process planning, comprehensive benefit calculation, and part design optimization. According to the system design objectives and design principles, the overall structure of the system is established, as shown in Figure 5, including three levels: user, business, and support layers:

(1) The user layer provides designers with a visual front-end operation interface, which can display the trigger buttons that can be operated during the software work process. At the same time, the data processing process of the business and support layers can be visually displayed to the designers in the form of charts;

(2) The business layer performs the system function in the background to realize the data exchange between the user and support layers. Its functions include parts editable dimensions extraction, feature identification, machining process planning, comprehensive benefit calculation, parts design optimization, *etc*.;

(3) The support layer provides data support for the prototype system, including the feature information database, machining process database, indicator database, *etc*.

System workflow

The main workflow of the system includes the following links. The system flow is shown in Figure 6.

(1) Connect to SolidWorks. In the Microsoft Visual Studio 2019 integrated environment, C# is used to build the system. First, the connection between the system and SolidWorks software must be established, and SolidWorks can be operated through the system;

(2) Model import and reconstruction. The user selects the part to be studied, and the system sends commands to import it into SolidWorks software. Then, the system obtains all the editable dimension information of the part by calling API functions and reconstructs the model by inputting initial dimensions;

(3) Manufacturing planning. The user will successively set the part material, plan the molding process (including the casting and forging process), and conduct the heat treatment process. After that, the system calls the corresponding API function to traverse the part, identify the features and extract the corresponding feature information. Finally, machining process planning and step sequencing are carried out based on the feature information;

(4) Comprehensive benefit calculation. The quantification equations of environmental impact and cost established in Section "Manufacturing planning" are written into the system to realize the comprehensive benefit calculation;

(5) Part design optimization. The initial design is optimized by taking the allowable dimension range of parts as the constraint condition, taking the dimensions of parts as the optimization variables, and aiming to reduce the comprehensive benefit;

(6) Performance analysis of the optimized model. With the help of the Simulation plug-in for SolidWorks, the working state is simulated for stress check to determine whether the optimized model still meets the requirements.

Table 5. Environment configuration for system development

Environment configuration	Description
Operating system	Win10
Integrated development tool	Microsoft Visual Studio 2019
Development software	SolidWorks 2020
Database	SQL Server 2014
Programming language	C#
Processor	Intel(R) Core(TM) i5-10200H CPU @ 2.40GHz

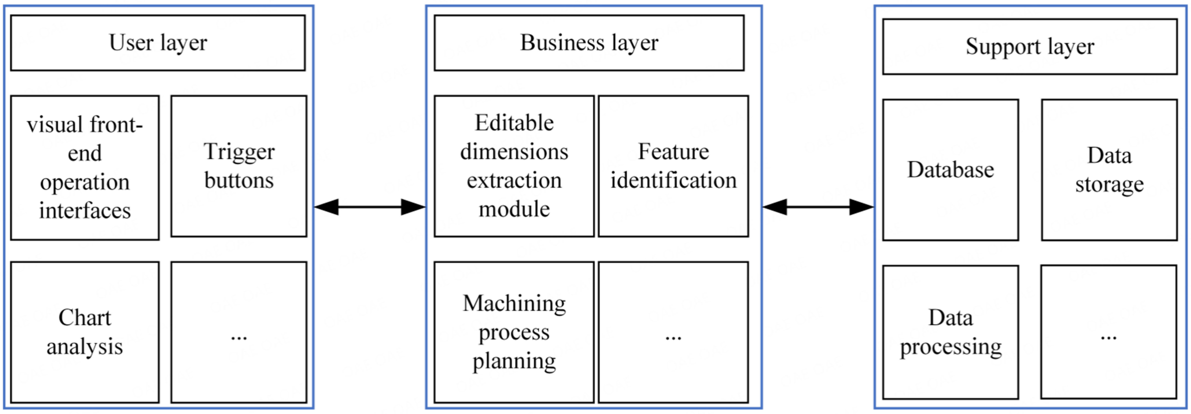


Figure 5. Structure of the system.

EXAMPLE VERIFICATION

This paper uses the intermediate shaft of belt conveyor reducer - sixth order step shaft as an example. The main interface of the system constructed in this paper is shown in Figure 7. The system can help designers quickly complete model reconstruction, manufacturing planning, and comprehensive benefit calculation. After that, with the comprehensive benefit as the optimization objective and dimensions as the optimization variables, the genetic algorithm realizes part design optimization. Finally, the performance of the optimized part is evaluated with the help of the Simulation plug-in for SolidWorks.

Model import and reconstruction

Select the sixth order step shaft from the model library and import it into SolidWorks. Click "Get editable dimensions" to get all model dimensions, save them to the SQL Server 2014 database, and then display them in the "dataGridView" control [Figure 8]. Under the premise of meeting the assembly requirements of the reducer, the designer enters the dimensions of the step shaft and its allowable symmetric tolerance. In this example, all symmetric tolerances are set to 1, and the desired model is obtained by clicking "Save".

Manufacturing planning

Triggering the "Manufacturing planning" first carries out material setting, molding process planning, and heat treatment process planning. The shaft is generally made of carbon steel and alloy steel. Round steel is generally used for shafts with smaller diameters. It is best to use cold-drawn steel directly. Forging blanks

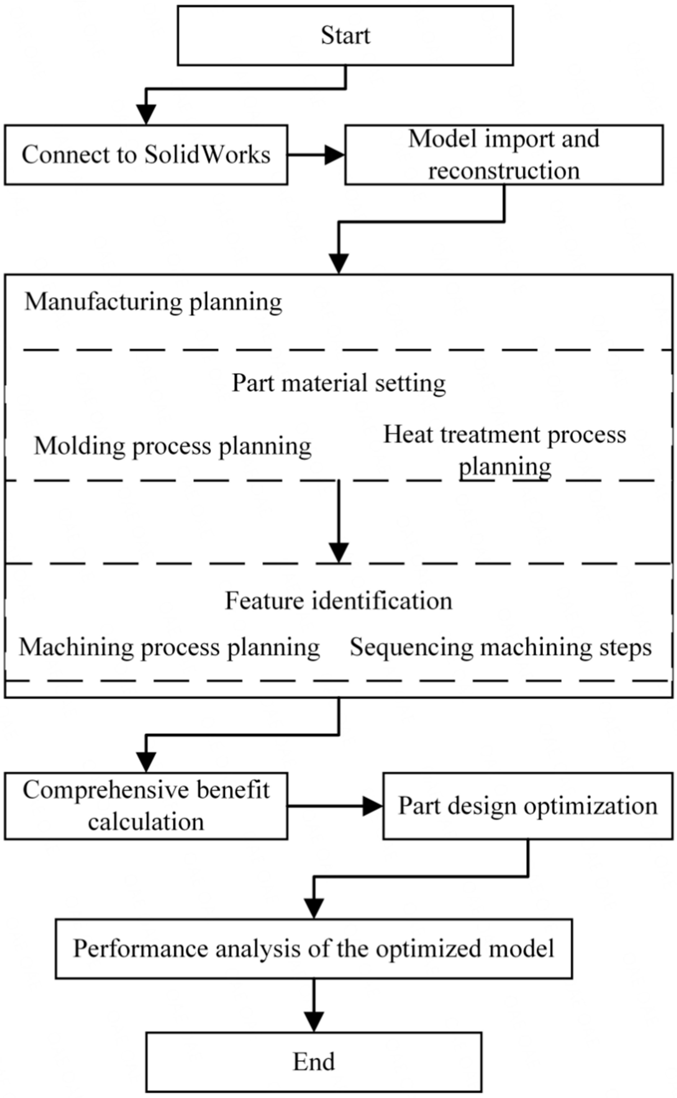


Figure 6. System workflow.

are used for shafts with large diameters or large step diameter variations. Because carbon steel is cheaper than alloy steel and less sensitive to stress concentration, heat treatment can improve its wear resistance and fatigue strength. So, most of the shafts are made of carbon steel. This paper selects a common carbon steel from the SolidWorks material library, and its model number is AISI 1045. Its properties are available from the SolidWorks material library, as detailed in Table 6.

In this paper, the forging process is selected for blank forming. The initial forging temperature is 1,200 °C, and the final forging temperature is 800 °C. For the blank heat treatment process, choose normalizing and quenching treatment. The heat treatment process information is shown in Table 7, according to reference[33].

Afterward, the part is planned for machining, and the feature identification is performed first. Set the machining accuracy for each feature. Then, the machining process planning is conducted. For the same machining equipment under the same type of machining, the principle of first roughing and then finishing

Table 6. AISI 1045 steel properties

Properties	Value	Unit
Elastic modulus	205	GPa
Poisson's ratio	0.29	N/A
Shear modulus	80	GPa
Density	7,850	kg/m^3
Tension strength	0.625	GPa
Yield strength	0.53	GPa
Allowable stress [σ] ≤ 173 MPa		

The data source is the SolidWorks2020 material library.

Table 7. Heat treatment process information of sixth order step shaft

Type of information	Normalizing	Quenching
Electrical consumption of standard process/kW·h	0.28	0.28
Process conversion factor	1.1	1
Heating mode factor	1	1.5
Part mode factor	1.6	1.6
Workpiece material factor	1	1
Loading factor	1.6	1.6

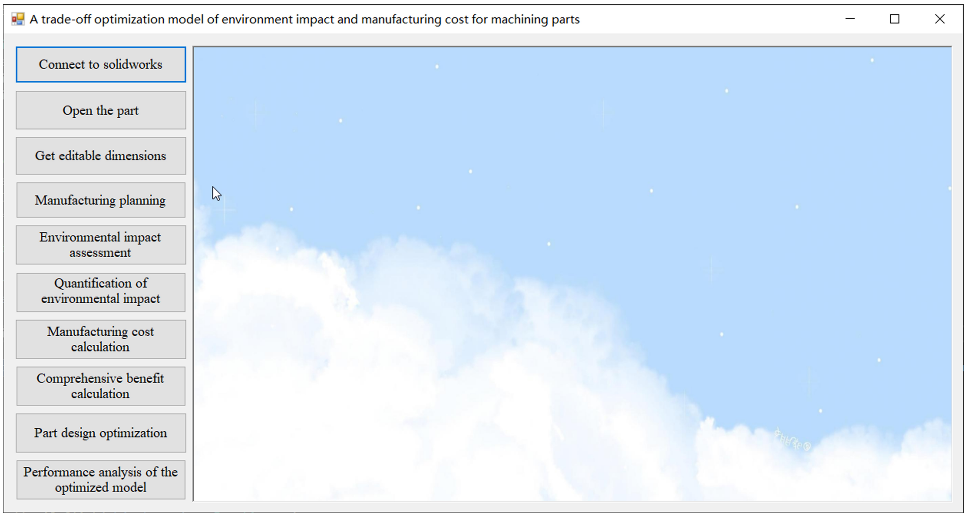


Figure 7. System main interface.

is used to sequence the steps to reduce the time of tool change, equipment change, and workpiece clamping to reduce the cost. The final machining process planning results are shown in Figure 9. The results of the complete machining process are shown in Table 8.

The comprehensive benefit calculation

The environmental impact indicators are from the GaBi database [Table 9].

Trigger the "Environmental impact assessment" button to calculate the environmental impact of the step shaft. The results of the environmental impact assessment are presented in Table 10.

Table 8. The machining process planning results of step shaft

ID	Machining feature	Machining accuracy	Process route	Machining equipment	Machining tool	Machining time
1	Cylinder surface	Finishing	Rough turning	CA6140	YT5	150.94
2	Cylinder surface	Semi-finishing	Rough turning	CA6140	YT5	50.31
3	Cylinder surface	Finishing	Rough turning	CA6140	YT5	322.01
4	Cylinder surface	Semi-finishing	Rough turning	CA6140	YT5	75.47
5	Cylinder surface	Finishing	Rough turning	CA6140	YT5	206.29
6	Cylinder surface	Finishing	Rough turning	CA6140	YT5	150.94
7	End face	Semi-finishing	Rough turning	CA6140	YT5	49.06
8	End face	Semi-finishing	Rough turning	CA6140	YT5	50.31
9	Cylinder surface	Finishing	Semi-finishing turning	CA6140	YT15	64.29
10	Cylinder surface	Semi-finishing	Semi-finishing turning	CA6140	YT15	21.43
11	Cylinder surface	Finishing	Semi-finishing turning	CA6140	YT15	137.14
12	Cylinder surface	Semi-finishing	Semi-finishing turning	CA6140	YT15	32.14
13	Cylinder surface	Finishing	Semi-finishing turning	CA6140	YT15	87.86
14	Cylinder surface	Finishing	Semi-finishing turning	CA6140	YT15	64.29
15	End face	Semi-finishing	Semi-finishing turning	CA6140	YT15	20.89
16	End face	Semi-finishing	Semi-finishing turning	CA6140	YT15	21.43
17	Cylinder surface	Finishing	Rough grinding	M1432A	Grinding wheel	55.36
18	Cylinder surface	Finishing	Rough grinding	M1432A	Grinding wheel	118.1
19	Cylinder surface	Finishing	Rough grinding	M1432A	Grinding wheel	75.66
20	Cylinder surface	Finishing	Rough grinding	M1432A	Grinding wheel	55.36
21	Cylinder surface	Finishing	Finishing grinding	M1432A	Grinding wheel	105.08
22	Cylinder surface	Finishing	Finishing grinding	M1432A	Grinding wheel	224.17
23	Cylinder surface	Finishing	Finishing grinding	M1432A	Grinding wheel	143.61
24	Cylinder surface	Finishing	Finishing grinding	M1432A	Grinding wheel	105.08
25	Keyway	Rough	Rough milling	XA5032	Cylindrical milling cutter	18
26	Keyway	Rough	Rough milling	XA5032	Cylindrical milling cutter	18.32

Table 9. Environmental impact indicators

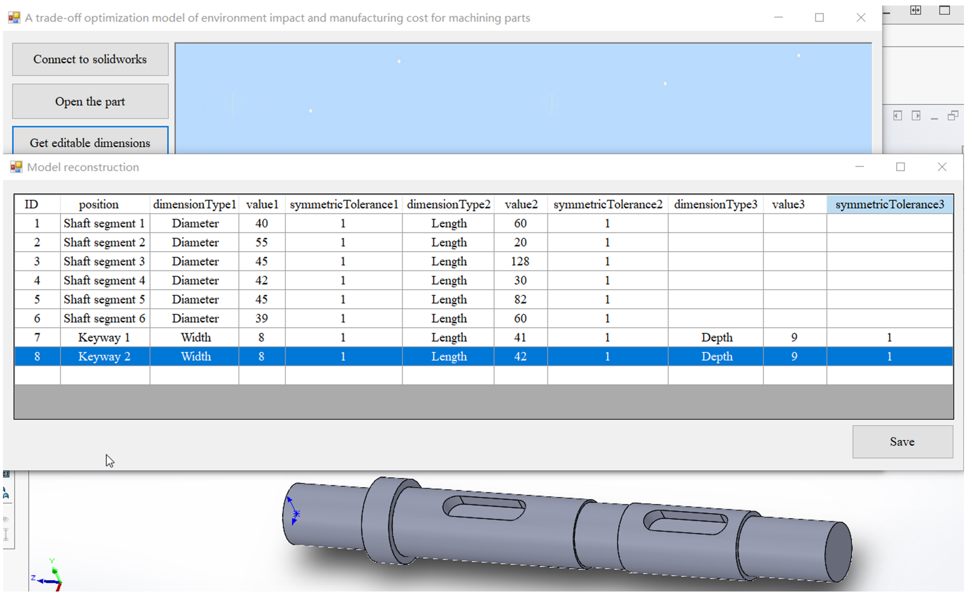
Type of environmental impact	AISI 1045 steel	Electricity	Unit
GWP	1.74E+00	7.91E-01	kg CO_2 eq.
AP	3.52E-03	2.32E-03	kg SO_2 eq.
POCP	6.71E-04	2.73E-04	kg Ethene eq.
EP	3.7E-04	2.34E-04	kg Phosphate eq.
ODP	1.39E-10	3.55E-12	kg R11 eq.
ADP e	2.87E-07	5.00E-08	kg Sb eq.
ADP f	1.71E+01	7.92E+00	MJ

GWP: Global Warming Potential; AP: Acidification Potential; POCP: Photochem. Ozone Creation Potential; EP: Eutrophication Potential; ODP: Ozone Layer Depletion Potential; ADP e: Abiotic Depletion elements; ADP f: Abiotic Depletion fossil.

Table 10. The results of the environmental impact assessment

Type of environmental impact	Value	Unit
GWP	2.86E+01	kg CO_2 eq.
AP	8.00E-02	kg SO_2 eq.
POCP	1.00E-02	kg Ethene eq.
EP	1.00E-02	kg Phosphate eq.
ODP	7.23E-10	kg R11 eq.
ADP e	2.61E-06	kg Sb eq.
ADP f	2.85E+02	MJ

GWP: Global Warming Potential; AP: Acidification Potential; POCP: Photochem. Ozone Creation Potential; EP: Eutrophication Potential; ODP: Ozone Layer Depletion Potential; ADP e: Abiotic Depletion elements; ADP f: Abiotic Depletion fossil.



ID	position	dimensionType1	value1	symmetricTolerance1	dimensionType2	value2	symmetricTolerance2	dimensionType3	value3	symmetricTolerance3
1	Shaft segment 1	Diameter	40	1	Length	60	1			
2	Shaft segment 2	Diameter	55	1	Length	20	1			
3	Shaft segment 3	Diameter	45	1	Length	128	1			
4	Shaft segment 4	Diameter	42	1	Length	30	1			
5	Shaft segment 5	Diameter	45	1	Length	82	1			
6	Shaft segment 6	Diameter	39	1	Length	60	1			
7	Keyway 1	Width	8	1	Length	41	1	Depth	9	1
8	Keyway 2	Width	8	1	Length	42	1	Depth	9	1

Figure 8. Model import and reconstruction process.

In this paper, the non-dimensional parameter A is 10^{12}. Trigger the "Quantification of environmental impact" to carry out weighted quantification of environmental impact assessment results. The quantification results are shown in Table 11. The quantified value of the total environmental impact of the step shaft in the raw material acquisition and manufacturing stages is 15.7. The largest impact is GWP, which accounts for about 40.14% of the total environmental impact.

Triggering "Manufacturing cost calculation" calculates the cost of the step shaft's raw material acquisition and manufacturing stages. The manufacturing cost of the step shaft is 67.07 yuan, of which the cost of the raw material acquisition stage is 21.54 yuan, and that of the manufacturing stage is 45.53 yuan.

Finally, trigger the "Comprehensive benefit calculation" to calculate the comprehensive benefit of the step shaft. Set the environmental impact and cost weighting factors as λ_1 = 0.53 and λ_2 = 0.47, according to reference[35]. The result of the comprehensive benefit calculation is shown in Figure 10. The comprehensive benefit value is 39.83, the environmental benefit value is 8.31, and the manufacturing cost-benefit value is 31.52.

Table 11. Quantification results of the environmental impact

Type of environmental impact	Value	Percentage
GWP	6.29E+00	40.14%
AP	1.96E+00	12.51%
POCP	1.80E+00	11.48%
EP	3.30E-01	2.11%
ODP	1.97E-05	0.00%
ADP e	5.00E-02	0.32%
ADP f	5.24E+00	33.44%
Total environmental impact value	1.57E+01	100%

GWP: Global Warming Potential; AP: Acidification Potential; POCP: Photochem. Ozone Creation Potential; EP: Eutrophication Potential; ODP: Ozone Layer Depletion Potential; ADP e: Abiotic Depletion elements; ADP f: Abiotic Depletion fossil.

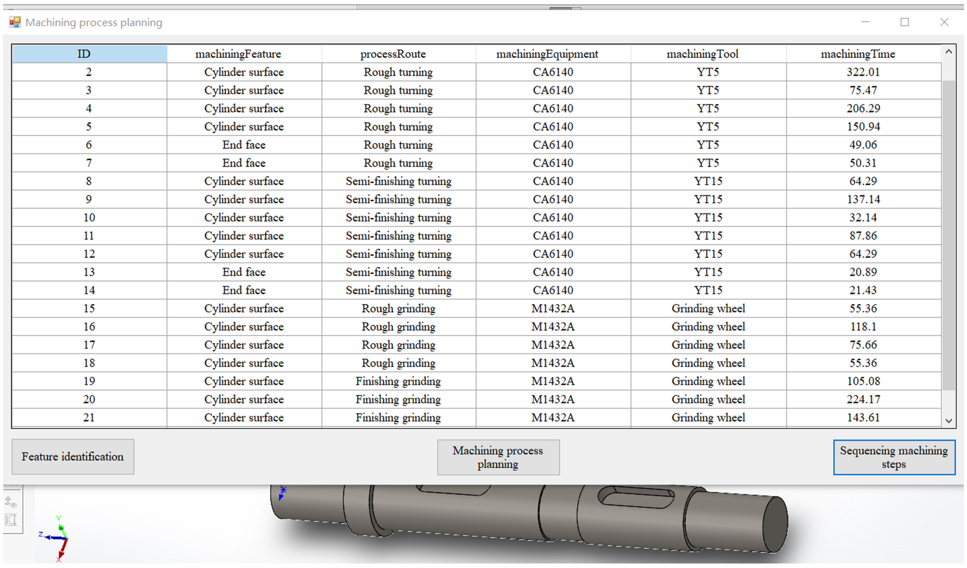


Figure 9. Machining process planning results.

Part design optimization

In this paper, the genetic algorithm is used to optimize part design. The initial population number is 150, the crossover probability between individuals is 0.7, the mutation probability is 0.06, and the termination condition is set to the iteration stops when the optimal solution is output. Trigger "Part design optimization" to start part design optimization. When iterating to the 155th generation, the system outputs the optimal solution. Record the comprehensive benefit and corresponding part dimensions at this time and input the dimensions into the model reconstruction interface [Figure 11]. Click "Save" to get the optimized model.

The results before and after optimization are shown in Table 12. The environmental impact benefit value in the table is obtained by multiplying the environmental impact quantitative value calculated by Equation (14) with λ_1. The economic benefit value in the table is obtained by multiplying the cost calculated by Equation (20) with λ_2. The comprehensive benefit value is the sum of the environmental impact benefit and cost benefit. After optimization, the comprehensive benefit of the step shaft improved by 1.63%, of which the environmental and economic benefits improved by 1.56% and 1.65%, respectively.

Table 12. Comparison of comprehensive benefits of step shaft

Type of benefit	Before optimization	Optimized	Improvement
Environmental	8.31	8.18	1.56%
Economic	31.52	31.00	1.65%
Comprehensive	39.83	39.18	1.63%

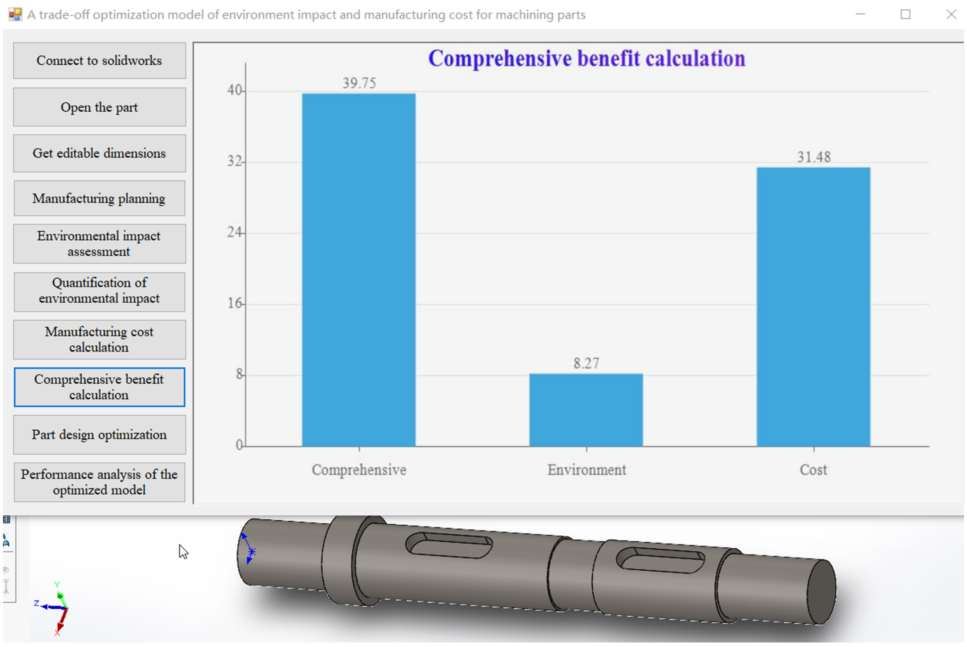


Figure 10. Comprehensive benefit calculation result.

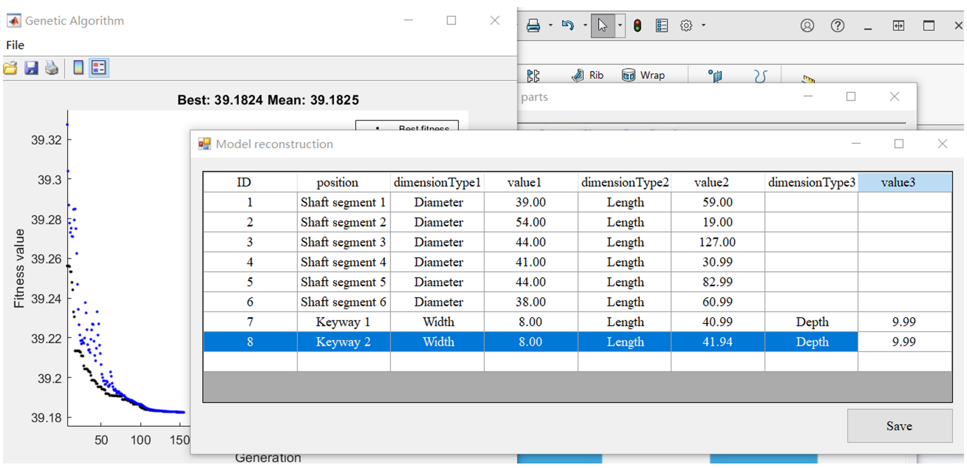


Figure 11. Part design optimization.

Performance analysis of the optimized model

In this paper, the Simulation plug-in for SolidWorks is used to implement the static analysis of the optimized part. The process of static analysis includes: (1) Create an example; (2) Set the material; (3) Add constraints; (4) Add fixes; (5) Delimit the mesh; and (6) Run the analysis. Through the secondary development of the Simulation plug-in, the above steps are realized in code, and the parametric interactive interface is designed. Before conducting the static analysis, it is necessary to calculate the force of the intermediate shaft gear first. The force calculation is as follows.

The motion and dynamic parameters of the belt conveyor reducer are shown in Table 13.

The number of big gear teeth on the intermediate shaft is Z_1 = 109, the modulus m_1 = 2, the number of pinion teeth is Z_2 = 27 and the modulus m_2 = 4. The force acting on the intermediate shaft gear is calculated by:

Transverse force:

$$F_t = 2 \cdot \frac{T_f}{d} \tag{26}$$

Radial force:

$$F_r = F_t \cdot \tan \alpha \tag{27}$$

Where T_f is the intermediate shaft torque, d is the intermediate shaft gear indexing circle, and α is the indexing circle pressure angle of 20°.

The calculated force result of the intermediate shaft gear is:
Big gear: transverse force F_{t1} = 4,136 N, radial force F_{r1} = 1,505 N.
Pinion: transverse force F_{t2} = 8,270 N, radial force F_{r2} = 3,010 N.

Among them, the force of the large gear is equivalent to the force of the keyway 1, and the force of the small gear is equivalent to the force of the keyway 2.

After the force calculation, the designer enters them into the parametric interactive interface. At the same time, the designer sets the name of the example and enters the mesh size. Click on "Analysis" to achieve static analysis of the step shaft. After the analysis is completed, its stress and displacement will be transferred to the current interface, and the analysis results are shown in Figure 12.

The maximum equivalent stress obtained from the simulation is 67.53316 Mpa, which is smaller than the permissible stress of the material, proving that the optimized shaft can meet the use requirements.

CONCLUSION AND FUTURE WORK

(1) To consider the environmental impact and manufacturing cost in the part design stage, this paper proposes a part design optimization method. It can realize the design optimization of parts from the perspective of the comprehensive benefit. Use the comprehensive benefit to measure whether the optimization of the part design has been realized. Based on this approach, a design optimization prototype system oriented to the comprehensive benefit is constructed. Take the intermediate shaft of the belt conveyor reducer - sixth order step shaft as a specific case. The results show that the comprehensive benefit of the optimized part improved by 1.63%, and the environmental and cost benefits improved by 1.56% and 1.65%, respectively;

Table 13. Belt conveyor motion and power parameter table

Axis name	Power (kW)		Torque (N·m)		Revolution speed (r/min)
	Input	Output	Input	Output	
Motor shaft	-	3.67	-	36.5	960
Input shaft	3.52	3.48	106.8	105.6	314.86
Intermediate shaft	3.21	3.18	450.8	446.6	68
Output shaft	3.05	3.02	1525	1510	19.1

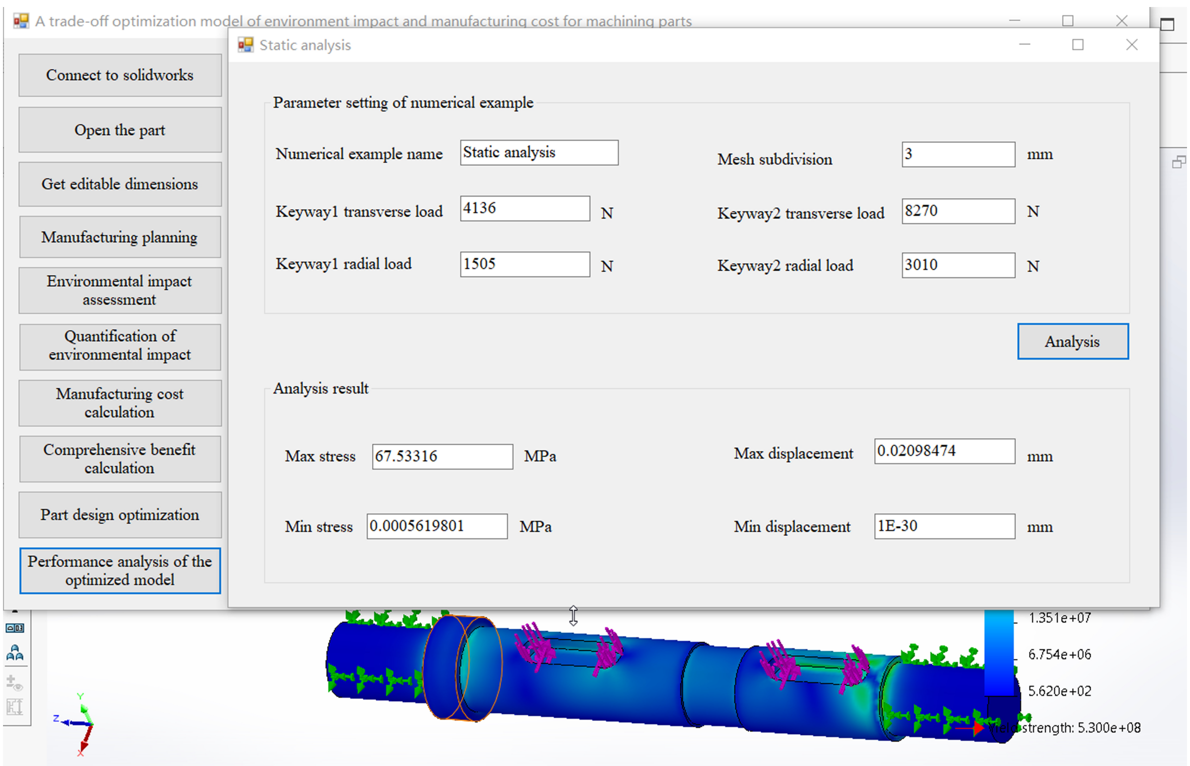


Figure 12. Static analysis result.

(2) Compared with the traditional optimization model, the feature information of parts can be fully utilized in this model. The environmental impact and cost can be calculated using the part model. Through the optimization of part design to improve the environmental impact and economic performance results. The optimization model improves the development efficiency of parts. It has a certain reference significance for realizing energy savings and cost reduction;

(3) During the cutting process, this paper applies the average power of the machine equipment to calculate the energy consumption. However, the power of different machine equipment running stages also varies, including no-load power, cutting power, and additional load power. Future research should improve the calculation of machine equipment energy consumption to obtain more accurate results. In addition, this paper only focuses on the two life cycle stages of raw material acquisition and manufacturing. The following research should solve the problem of the life cycle data collection being difficult to complete and accurate and expand the research boundary to the whole life cycle stage.

DECLARATIONS

Authors' contributions

Conceptualization, methodology, validation, system construction, original draft preparation: Tao K
Supervision, review and editing, formal analysis: Zhang L
Methodology, investigation: Zheng Y, Zhu K
Data curation, investigation: Fang J, Su J

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest. Zhang L is an Editorial Board Member of the journal *Green Manufacturing Open*.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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