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MULTI-OBJECTIVE OPTIMIZATION DESIGN OF LOW-CARBON PRODUCTS BASED ON USER-DRIVEN APPROACH IN PARTS RECYCLING: EXAMPLE FROM SMARTPHONE INDUSTRY

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Abstract. *The multi-objective optimal design of low-carbon products is of great importance to the effective reduction of carbon emission during the product life cycle and the development of low-carbon economy. In this paper, the modular model has been utilized to optimize the system. The main content of this research is as follows. (a) From the user-driven perspective, a model for designing the low-carbon product which can satisfy the needs of the user, enterprise and government as well as recycle the parts has been built. (b) The greedy algorithm has been used to solve the problem of multi-objective optimal design involving multiple subjects. (c) With smart phone as an example, a feasible scheme has been proposed for designing low-carbon products. As shown by the research result, such scheme based on the user-driven perspective and parts-recycling situation has been realized. It can not only reduce the production cost of the enterprise but also satisfy the users' demand for high-performance low-carbon products. Moreover, it can cater to the low-carbon policies of the government, thus realizing the green and sustainable development.*
Keywords: Low-carbon product design, User-driven approach, Parts recycling, Multi-objective optimization

1. **Introduction.** As the main source of green-house gas emissions (GHG), energy consumption has surged with the rapid economic development. In 2016, China's whole energy consumption is approximately 4.36 billion tons of standard coal, which makes up for more than 1/5 of the global total energy consumption [1]. Considering the fact that excessive carbon consumption leads to the excessive production of carbon dioxide-based greenhouse gas emissions, it is necessary to coordinate the use of raw materials, parts production, assembly, and recycling in terms of sources, which is called product design, to effectively reduce the energy emissions in the section of the product's whole life cycle. Meanwhile, trying to implement the strict carbon tax policy, as well as the low-carbon product transformation, has brought important theoretical and practical value for enterprises. It not only saves cost and achieves green production but also reduces carbon emissions, maintaining the ecological environment and sustainable development.

In recent years, researches on low-carbon product have made great achievement and significant progress. Reviewing the referring literature, the multi-objective and dynamic methods are the main technologies in the study of low-carbon product [2].

Wang et al. and Kuo et al. set carbon footprint and product cost as the optimized objective; algorithms such as the backtracking algorithm and greedy algorithm are used to solve the bi-objective multi-constraint problem [3,4]. Furthermore, Su et al. developed a bi-level optimization process that searches the optimal assembly structures to estimate the carbon emissions and product cost, as well as optimize the supply chain configuration [5]. Chiang and Che took the electronic products MP3 for example regarding performance, design time and cost as objectives to solve the low-carbon design issues by greedy algorithm [6]. Xu et al. introduced carbon tax into trilateral requirement model, in other words, enterprises, users, and government [7]. Consequently, it handled this optimization problem starting from enterprise requirement model and attained low-carbon lathe design schemes satisfying triple requirements by different algorithms.

From the literature above, the product performance, cost, carbon emissions are the main ones to design the low-carbon product. However, few references studied low-carbon product optimization design problem based on user-driven approach, and few scholars focused on the return of parts when considering low-carbon product design problem. In fact, Lalicic and Dickinger proposed the feasibility of user-driven approach in smartphone application and the qualitative analysis shows the necessity of user-driven innovation [8]. Wang, Nien and Zhao emphasized the importance of low-carbon product design, refined the user needs by adopting modular methods, and further optimized the design schemes in the view of user [9,10].

At the same time, the significance of recycling has generally aroused extensive attention among entrepreneurs and research scholars. As early as in 1997, Zheng and Yuan highlighted the importance of recycling for solving the increasingly serious environmental pollution problems [11]. Martinho et al. took the example of a smartphone and tablet computer to illustrate the importance of improving recovery and recycling rates [12]. Entezaminia et al. and Wan et al. attempted to introduce recycling factors into the total production plan in the green supply chain implemented by government, and indicated that recycling is conducive to maintaining long-term profits [13,14]. Referring to the issues of low-carbon product design, previous studies usually focused on the innovation and optimization of low-carbon product design that starts from the enterprise. It is worth noting that concentrating from the users' perspective on the low-carbon product design is of much significance, which is also a necessity to analyze the impact of both user-driven and parts recovery.

The contributions of this paper can be concluded as follows. (a) A modular family model catering to the demands of users, enterprises, and the government is established. Triple multi-objective models in parts recycling sites are built through the four-level structure. (b) Focusing on user-driven design in low-carbon products, this paper regards the common constraints as the starting point. Then, it exemplifies schemes that manifest user needs and further takes these into triple models to screen out the low-carbon products design schemes. (c) With the smartphone industry as an example, the application is exemplified to obtain the final design schemes. Moreover, through the comparisons between the user-driven and the enterprise-driven approach, several decision-making suggestions and management inspiration are put forward.

The remainder of the paper is structured as follows. Section 2 describes research tasks and some assumptions. In Section 3, multi-objective models from the view of three parts are built. Section 4 provides a solving approach and specific flow chart. Section 5 proposes the smart-phone case study and the experimental results. Finally, concluding remarks and further extension to this work are outlined in Section 6.

2. **Problem and Assumptions.**

2.1. **Problem description.** Low-carbon product design is a multi-objective optimization process which coordinates user benefits, enterprise profits and social welfare.

In the constitution, this paper establishes a four-layer-structure divided by recyclability, mainly functional modules and various specific modules. According to the recyclability, recyclable and non-recyclable parts are divided; secondly, through the functional modules, it can get three different types, that is, core module aiming to achieve its main module function, accessory module containing specified modules from the main structure according to certain rules, optional module content to a lot special user requirement; finally, it is divided into a number of specific module systems with the same function but different parameters such as performance, and user cost. By the way, to ensure the realization of objective functions in the models, as well as the diversity of product schemes, this paper sets out the common constraints. That is, a product scheme consists of several module entities that are chosen from each module once owing to many alternative construction schemes, as is shown in Figure 1.

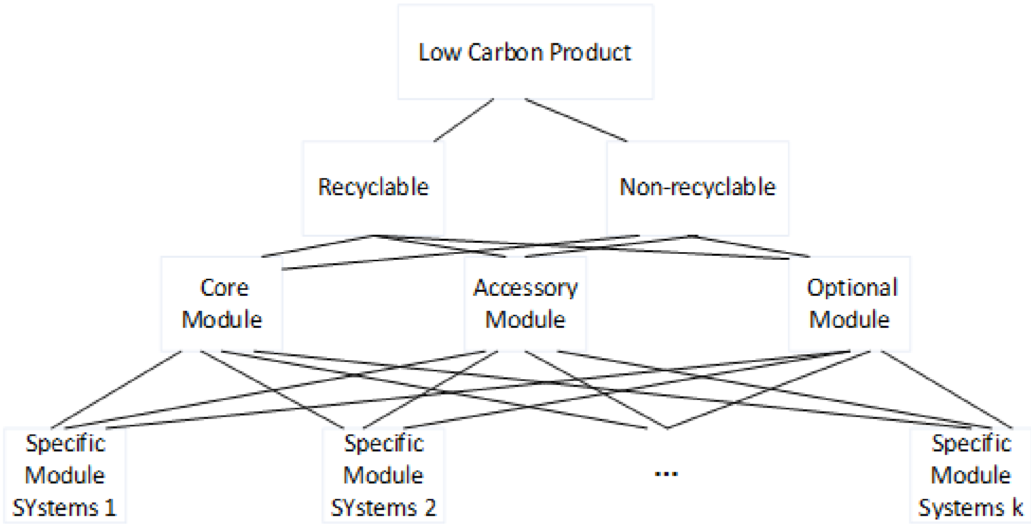

FIGURE 1. Four-layer-structure of the low-carbon product

2.2. **Symbol description.** (1) M_{1jkl} denotes a module entity that is of the jth main functional module, kth specific module system rank of l in recyclable situation, while M_{2jkl} denotes a module entity in non-recyclable situation, $j = 1, 2, \ldots, J$, $k = 1, 2, \ldots, K$, $l = 1, 2, \ldots, L$.

(2) $x_{ijkl} \in \{0, 1\}$ is a binary decision variable denoting whether a low-carbon product includes the module entity M_{ijkl}, $i = 1, 2, \ldots, I$, $j = 1, 2, \ldots, J$, $k = 1, 2, \ldots, K$, $l = 1, 2, \ldots, L$.

(3) P denotes the performance. ω_d is the weight vector of dth performance. $\gamma_{ijkl,d}$ is the correlation degree between M_{ijkl} and dth performance used by "strong", "less strong", "medium", "weak" or "irrelevant" in natural language, $d = 1, 2, \ldots, D$.

(4) C_1 denotes the sum of parts production cost and product assembly cost.

(5) ξ_1 denotes a ratio of carbon tax to product cost arising from parts production and product assembly, and ξ_2 denotes the government carbon tax rate.

(6) V_1, V_2 separately denote mill price, user price, and ΔV is the price difference.

(7) V_r denotes recovery subsidies, $r = 1, 2, \ldots, R$. p_{jk} denotes the recovery price in recyclable situation, μ_j denotes the subsidy rate that government offers by jth main functional modules, $j = 1, 2, \ldots, J$, $k = 1, 2, \ldots, K$.

(8) G denotes the enterprise's expected profit, and η is the expected profit rate.

(9) c_{ijkl}, e_{ijkl} separately denote module cost and carbon emissions in parts production. c_z, e_{av} denote the mean cost and carbon emissions in assembly process.

(10) k_e represents the carbon tax ratio converting e_{ijkl} into t_{ijkl}, denoting the supposed carbon tax paid by carbon emissions during production and assembly process.

2.3. **Model assumptions.** For the sake of analysis and research, we propose the following assumptions.

(1) The total amount of the carbon emissions arises from energy and raw materials in the part production process and the carbon emissions in product assembly process.

(2) The product cost is the sum of the part production cost, the product assembly cost and parts recovery cost regardless of other factors.

(3) The product carbon tax is equal to the sum of the carbon taxes generated during the part production process and product assembly process.

(4) There is a certain proportion of enterprise profits and product costs [9].

3. **Model Construction.** Based on user-driven design, this paper first builds user model, and then constructs the enterprise model and government model. In view of constraints, the left side indicates the boundary index and the right one means the specific expression.

3.1. **User requirement model.**

$$\min f_1 = \left((1+\eta)\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} c_{ijkl}x_{ijkl} + c_z \times \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl} - 1\right)\right.\right.$$
$$\left.\left.+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}(1-\mu_j)p_{jk}x_{1jkl}\right) + k_e\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} e_{ijkl}x_{ijkl} + k_e e_{av} + \Delta V\right)$$

$$\max f_2 = \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl}\sum_{d=1}^{D}(\omega_d\gamma_{ijkl,d})\right)$$

$$\text{s.t. } V_2 \geq (1+\eta)\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} c_{ijkl}x_{ijkl} + c_z \times \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl} - 1\right)\right.$$
$$\left.+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}(1-\mu_j)p_{jk}x_{1jkl}\right) + k_e\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} e_{ijkl}x_{ijkl} + k_e e_{av} + \Delta V \quad (1)$$

$$p \leq \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl}\sum_{d=1}^{D}(\omega_d\gamma_{ijkl,d}) \quad (2)$$

The first objective function represents the user price, and the second one represents performance. The constraint (1) represents the user price, which is the combination of the mill price and the price difference. And the mill price consists of the product cost, the carbon tax and the enterprise profit. Constraint (2) is centered on performance. When the performance index is higher, it shows better function.

3.2. **Enterprise requirement model.**

$$\max g_1 = \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl}\sum_{d=1}^{D}(\omega_d\gamma_{ijkl,d})\right)$$

$$\min g_2 = \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} c_{ijkl}x_{ijkl} + c_z \times \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl} - 1\right)\right.$$
$$\left.+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}(1-\mu_j)p_{jk}x_{1jkl}\right)$$

$$\text{s.t. } C_1 \geq \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} c_{ijkl}x_{ijkl} + c_z \times \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl} - 1\right) \quad (3)$$

$$p \leq \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl} \sum_{d=1}^{D}(\omega_d \gamma_{ijkl,d}) \tag{4}$$

$$\xi_1 \geq \left(k_e \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} e_{ijkl}x_{ijkl} + k_e e_{av}\right) \Bigg/ \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} c_{ijkl}x_{ijkl} + c_z \times \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl} - 1\right) + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}(1-\mu_j)p_{jk}x_{1jkl}\right) \tag{5}$$

$$G \leq \eta\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} c_{ijkl}x_{ijkl} + c_z \times \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl} - 1\right) + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}(1-\mu_j)p_{jk}x_{1jkl}\right) \tag{6}$$

The first objective function represents the performance, and the second one is the product cost, including the part production cost, the product assembly cost and the part recovery cost. The constraint (3) represents the cost of part production and product assembly, including costs and taxes in part production and product assembly. Constraint (4) are the same as the (2) in user model. Constraint (5) represents a ratio of carbon tax to product cost arising from parts production and product assembly, and the constraint (6) indicates the expression of the firm's profit.

3.3. **Government requirement model.**

$$\min h_1 = \left((1+\eta)\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} c_{ijkl}x_{ijkl} + c_z \times \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl} - 1\right) + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}(1-\mu_j)p_{jk}x_{1jkl}\right) + k_e \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} e_{ijkl}x_{ijkl} + k_e e_{av} + \Delta V\right)$$

$$\max h_2 = \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} \mu_j p_{jk} x_{1jkl}\right)$$

$$\text{s.t. } V_2 \geq (1+\eta)\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} c_{ijkl}x_{ijkl} + c_z \times \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl} - 1\right) + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}(1-\mu_j)p_{jk}x_{1jkl}\right) + k_e \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} e_{ijkl}x_{ijkl} + k_e e_{av} + \Delta V \tag{7}$$

$$p \leq \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl} \sum_{d=1}^{D}(\omega_d \gamma_{ijkl,d}) \tag{8}$$

$$\xi_2 \geq \left(k_e \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} e_{ijkl}x_{ijkl} + k_e e_{av}\right) \Bigg/ \left((1+\eta)\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} c_{ijkl}x_{ijkl} + c_z \times \left(\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{ijkl} - 1\right) + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}(1-\mu_j)p_{jk}x_{1jkl}\right) + k_e \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} e_{ijkl}x_{ijkl} + k_e e_{av} + \Delta V\right) \tag{9}$$

The first objective is the user price, and the second is the government subsidy. The constraint (7) is the user price constraint, while the constraint (8) is the performance constraint, which both are the same as the user model. Constraint (9) represents carbon-tax rate. Moreover, the government often defines the carbon tax rate based on the user price; in other words, the carbon-tax rate is the ratio of carbon tax to user price.

4. **Solving Strategy.** While solving the problem, the research firstly introduces the genetic algorithm in the Matlab2014a environment to find out several Pareto solution sets by objectives. When tested by constraints, in the view of the distinct decision variables in this paper, many situations turn out to be empty sets. According to the multi-objective planning of the key target method and the hierarchical sorting method with tolerance value, this paper proposes the greedy algorithm. In terms of the multi-objective optimization theory, the algorithm will absolutely find the effective solution of the original problem. In order to get a more accurate solution set, this paper proposed the following flow chart in the process of low-carbon product design, as is shown in Figure 2.

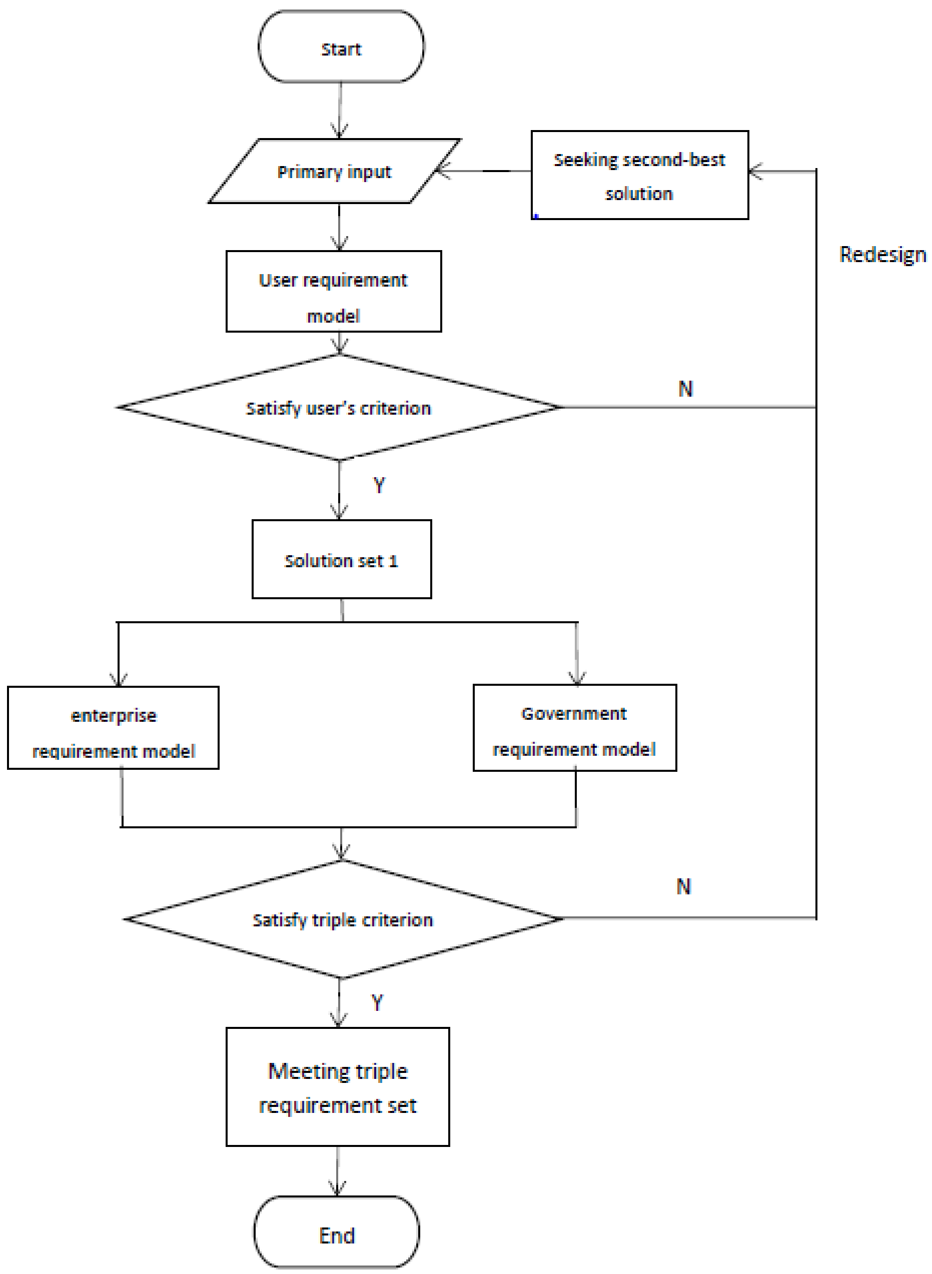

FIGURE 2. Solving strategy

Firstly, in terms of public constraints, there exist hundreds of different product schemes called P1. Secondly, in user model, product schemes generated by screening out the suitable schemes from P1 by constraints are named P2, while objectives are measured by a weighted order, and the better half of solutions is selected by greedy algorithm, P3. Thirdly, in enterprise model, it is necessary to find schemes content to constraints from the set P3 and record it as set P4. Among P4, the goal is to filter out the better half of the solution set by objective functions and regard those suitable ones as P5. Finally, in government model, steps are made to pick out the proper schemes from the set P5 that fit the constraints, P6. Successfully, this paper gets the ultimate solution set that better half of the solutions is chosen from the set P6 by the weighted order of objectives, satisfying triple requirements. If not reasonable, seeking the second-best solution set through the algorithm flow chart is required.

5. **Case Study.**

5.1. **Basic data.** In this paper, an electronic product industry-smartphone is adopted, composed of 37 basic parts that business decision makers tend to recycle 14 parts, and the recovery rate is 37.83%. When considering the low-carbon design, the relevant parameters are as follows.

(1) User requirements: This research tries to get user price difference $\Delta V = 648.2$ by surveying according to practical market price. Parameter is defined as $V_2 = 3300$.

(2) Enterprise requirements: In assembly process, mean cost $c_z = 10.02$, mean carbon emission $e_{av} = 2.09$, and ratio $k_e = 0.1$. The recovery price of the RF section is $p_{11} = 32$, the logical one $p_{12} = 28$, the power supply one $p_{23} = 35$, the interface one $p_{24} = 11$. Parameters are defined as $C = 2050$, $P = 36.5$, $\xi_1 = 0.05$, $\eta = 19.2\%$, $G = 395$.

(3) Government requirements: The subsidy rate for the core module is $\mu_1 = 0.7$, for the accessory module $\mu_2 = 0.5$, for the optional module $\mu_3 = 0.3$. Parameters are defined as $\xi_2 = 0.0294$.

Other specific parameters are shown in Appendix (Table A.1). When it comes to the calculation of performance, the enterprise decision maker tends to use the safety, life cycle, quality and the memory capacity to express; using analytic hierarchy process we get the weights $\omega = \{0.234, 0.25, 0.388, 0.128\}$. The correlation degree is listed in Appendix (Table A.2).

5.2. **Result analysis and discussion.** In the consideration of multi-objective issue based on user-driven approach, this research makes full use of different module entities to achieve the product schemes' diversity to realize product adaptability. From the corresponding schemes, seeking the design variable index is supposed for customer satisfaction [15]. Solved by flowing chart, business decision makers tend to determine the weight of 0.5. Schemes below are satisfying trilateral requirement based on user-driven approach. Here are listed in detail in Table 1.

For the comparative analysis, the product design schemes driven by the enterprise, firstly from the enterprise model, have been studied. It comes clear that the process is supposed to repeat in turn to get the final schemes. Specifically, business decision

Table 1. Schemes based on user-driven approach satisfying trilateral requirement

Scheme number	Modular configuration	User price	Cost	Performance
11	M_{1111}, M_{1122}, M_{1231}, M_{1242}, M_{2112}, M_{2122}, M_{2231}, M_{2243}, M_{2351}	3205.994	2026.42	38.678
139	M_{1111}, M_{1121}, M_{1231}, M_{1242}, M_{2112}, M_{2122}, M_{2231}, M_{2243}	3205.653	2026	37.348

Table 2. Schemes based on enterprise-driven approach satisfying trilateral requirement

Scheme number	Modular configuration	User price	Cost	Performance
139	M_{1111}, M_{1121}, M_{1231}, M_{1242}, M_{2112}, M_{2122}, M_{2231}, M_{2243}	3205.653	2026	37.348

makers tend to determine the same weight. There exists a scheme satisfying the trilateral requirement based on the user-driven approach that is listed in detail in Table 2.

Based on this situation, schemes regarding smartphone are not the same. Performance index based on the user-driven approach is generally high compared with enterprise-driven one, while the cost and price indexes are in small fluctuation. At the same time, the user driven impact contributes to the decline of profits and user price. However, the fluctuation is controlled within 5% that is still in the acceptable range of the enterprise.

In conclusion, low-carbon product design based on user-driven approach is for the better use of resources and raw materials, reducing the unnecessary costs even energy consumption. In a short period, the enterprise needs to transform a certain profit margin to users, leading to the profit decline. However, in the long-term development, the overall profit is increasing, which helps improve user loyalty and maintain the long-term purchase relationship to strengthen the purchasing power. As a result, it helps to use resources as little as possible to meet the user's aspirations, contributing to the maximization of the social welfare and long-term coexistence.

6. Conclusions.

Nowadays, the environment has been constantly deteriorating, and thus the low-carbon product design faces enormous challenges, especially the serious extant parts-recovery problems in China. Considering the recently related researches on the optimization design theory of low-carbon products, this paper may be the first kind to consider the multi-objective model with three-party demands, simultaneously introduces the parts recycling into the product design. Further efforts are made to assess the exact influence of the user-driven approach. Conclusions can be reached as follows.

(a) What can be indicated is that the user-driven design is conducive to lifting the overall profits. It is recommended that enterprises are supposed to design from the user's prospective, improving the current purchasing loyalty and consuming power as well as the core competitiveness which benefits the long-term co-development.

(b) The introduction of parts recycling is in the line with national policy guidance, catering to the modern consumption concept. Users are likely to follow with their interests in protecting the environment. It is asked that enterprises need to consider the parts' recyclability to reduce unnecessary carbon emissions and energy consumption.

(c) In the premise of the user-driven approach, this research takes the requirements of three parts into account in turn, seeking the overlapping ones for the better coordination of user experience, enterprise profit, and social welfare to reach the tripartite-win situation.

In this paper, we find that the calculation of carbon emissions from low-carbon products (smartphones, etc.) is not precise enough and needs to be further improved.

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Appendix

Table A.1

Recycle	Part section	Entity	Parts	c_{ijkl}	e_{ijkl}	V_r	Type
Y	RF	M_{1111}	6.7	307.34	196	44.8	1
		M_{1112}	7.36	279.24	178.1	44.8	
Y	logical	M_{1121}	9.10.19	70.62	106.3	58.8	1
		M_{1122}	5.9.10	71.04	104.7	58.8	
Y	power	M_{1231}	23.35	247.46	127.3	35	2
Y	interface	M_{1241}	1.2.3.14.21.22.27	348.68	48.7	38.5	2
		M_{1242}	1.2.3.14.21.22.32	321.78	44.9	38.5	
N	RF	M_{2111}	8.24	305.64	216		1
		M_{2112}	8.31	281.61	158.7		
N	logical	M_{2121}	25.26	73.75	124.8		1
		M_{2122}	25.29	73.97	115.7		
N	power	M_{2231}	11.12	282.96	138.6		2
		M_{2232}	11.30	265.17	125.7		
N	interface	M_{2241}	4.13.15.16.20.34	377.51	56.3		2
		M_{2242}	13.15.16.17.20.34	411.28	42.4		
		M_{2243}	4.13.15.16.33.34	370.12	46.3		
		M_{2244}	13.15.16.17.33.34	436.35	40.2		
N	optional	M_{2351}	18.28	18.94	13.5		3
		M_{2352}	28.37	26.63	9.7		

Note: (a) In the module type column, "1" denotes core module, "2" denotes accessory module, "3" denotes optional module. (b) The subscript of M_{ijkl} corresponds to the subscript of x_{ijkl} in computation.

Table A.2

Recycle	Parts	Entity	Safety	Life	Quality	Memory	Type
Y	RF	M_{1111}	4	9	4	4	1
		M_{1112}	4	7	0	1	
Y	logical	M_{1121}	1	7	1	0	1
		M_{1122}	4	9	1	1	
Y	power	M_{1231}	1	4	9	7	2
Y	interface	M_{1241}	4	4	7	1	2
		M_{1242}	7	7	9	4	
N	RF	M_{2111}	7	9	4	4	1
		M_{2112}	4	9	4	4	
N	logical	M_{2121}	7	4	1	4	1
		M_{2122}	7	9	1	0	
N	power	M_{2231}	7	4	4	1	2
		M_{2232}	1	4	4	7	
N	interface	M_{2241}	7	1	4	1	2
		M_{2242}	7	1	0	0	
		M_{2243}	9	1	0	4	
		M_{2244}	7	1	4	4	
N	optional	M_{2351}	4	4	1	4	3
		M_{2352}	4	1	0	1	