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Multi-objective Optimization for Performance, Cost and Carbon Tax of Low-carbon Product

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Abstract: Low-carbon economy and low-carbon product have attracted great attention in the world field. Introducing carbon tax system into product design could monitor and control carbon emissions of products effectively. The objective of this research is to build product's multi-objective optimization design models with performance, cost and carbon tax as optimization objectives. A formula for calculating carbon tax of product was given and then a product optimization design model driven by carbon tax was built which combined with the performance-driven model and the cost-driven model to constitute the low-carbon product multi-objective optimization design model. NSGA-II was employed to find the Pareto optimal design schemes. A case study of low-carbon product configuration optimization design for touring bicycle was given. The result shown that 13 configuration schemes satisfying the given requirements of performance, cost and carbon tax were found. This could be a good reference for enterprise to conduct low-carbon production.

Key words: Low-carbon product, carbon tax, performance, cost, multi-objective optimization

INTRODUCTION

In the 21 century, product design is confronted with severe challenges both of environmental deterioration and sharp drop in earth resources. Low-carbon product design has become a hot spot attracting attentions from academia and enterprise. Practice indicated that it was hard to thoroughly resolve the issue of carbon emissions from enterprise without social supervision. Carbon tax system has been taken seriously by every country because it is an effective mechanism to enable government to monitor and control the carbon emissions from enterprise (OECD, 1996).

It was market orientation that satisfied the customer's demands that traditional product design ideas paid close attention to, however, the social requirements, such as low carbon emissions, were often neglected. Devanathan *et al.* (2010) believed that the modern product design methodology had shifted the viewpoint from focusing on performance and cost of product to seeking a balance among economy, environment and society.

In this study, carbon tax system was introduced into product design and low-carbon product optimization design models that satisfied the enterprise's demands on performance, cost and allowable carbon tax were built. Furthermore, the low-carbon product optimization design models that driven by performance and cost (including carbon tax) could be derived. Non-dominated sorting genetic algorithm (NSGA-II) (Deb *et al.*, 2002) was employed to find the Pareto optimal set satisfying the requirements of performance, cost and carbon tax. NSGA-II is an efficient algorithm developed by Deb *et al.* (2002) to handle multi-objective optimization problems. It is used wildly in many fields because of its parameterless and simple properties.

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EARLY WORK

In recent years, researches on low-carbon product design have attracted broad attention and scored gratifying progress. Ameta *et al*. (2009) presented a Carbon Weight Tolerance Analysis (CWTA) method for allocating carbon emissions of the parts in manufacturing. Song and Lee (2010) developed a low-carbon design system for electronic products. Devanathan *et al*. (2010) developed a function impact matrix to correlate environmental impacts with product function. Qi and Wu (2011) studied low-carbon technologies and presented a dynamic configuration application model. Branker *et al*. (2011) considered the energy and environment cost in optimizing the machining parameters and presented a machining microeconomic model. Zhang *et al*. (2012) proposed an easier way of calculating carbon footprints of products. Sun *et al*. (2012) provided a described method for carbon emissions in manufacturing process of complex equipment. In the context of low-carbon economy, Wang *et al*. (2012) presented a multi-objective mixed integer linear programming model to design closed-loop logistics network in remanufacturing.

In conclusion, the previous related studies mainly focused on calculating the carbon footprints, and product green design. In recent years, researches have expanded to low-carbon product modular design or low-carbon product configuration design. For example, based on carbon emissions list of parts or modules, the key factor that influenced carbon emissions could be found by various analysis and evaluation methods. Generally, the problematic parts were replaced or redesigned, or a low-carbon design scheme was determined in early stage. That can be regarded as a derived branch of product green design. However, work about how to introduce carbon tax into product design models, what effects the carbon tax will have on performance and cost and how to realize low-carbon product design that satisfies the requirements of performance, cost and carbon tax was seldom reported.

CARBON TAX SYSTEM AND PRODUCT CARBON TAX CALCULATION

Carbon tax system: Carbon tax system is a tax system by which governments levy tax on the consumption of hydrocarbon fuel (coal, petroleum and natural gas) to lessen carbon emissions.

In the early 1990's, carbon tax system was successively carried out in Finland, Holland, Norway, Sweden, Denmark, Switzerland, etc. Later, Slovenia, Italy, Germany, UK, France *et al*. also carried out carbon tax system. Boulder, Colorado in the USA, British Columbia and Quebec in Canada carried out carbon tax system in November 2006, July 2008, October 2007, respectively (Cui, 2010). Carbon tax scheme in Japan was enacted in October 2005 and was carried out on January 1, 2007 (Wang *et al*., 2011). The EU emissions trading scheme was launched on January 1, 2005 towards heavy industrials to compel them to conserve energy and reduce emission (Grubb and Neuhoff, 2006). Australia passed a carbon tax legislation in November 2011 and planned to carry out it on July 1, 2012 (Australian Government, 2011). Recently, South Africa Government suggested to collect carbon tax from January 1, 2015 (Gordhan, 2013). In China, the carbon emissions would be reduced by 17% in 2015 relative to 2010 (SC, 2011). And an interim measures of low carbon product certification management was enacted in March 2013 (ND and RC, 2013).

Definitions and calculation of product carbon tax: This study gave some definitions about product's carbon tax based on available literatures as follows: (a) Rated carbon tax of product [CT]: Being converted from the rated carbon emissions [CE] allocated to the enterprise by government according to its production status, (b) Practical carbon tax of product $CT^{practical}$: Being converted from the practical carbon emissions $CE^{practical}$ produced in the production process of product, (c) Calculated carbon tax of product CT: Being figured out with calculation method or test method according to product design scheme. It was called carbon tax for short, (d) Carbon tax rate of product CR: The carbon tax rate fell into two categories, carbon tax rate of production stage in enterprise and carbon tax rate of product full life cycle. The former was divided into carbon tax rate of basic cost and carbon tax rate of outgoing product. Carbon tax rate of basic cost (called carbon tax rate for short) could be described as $CR^{C0} = CT/C_0$, where, C_0 is the pre-tax cost (barring carbon tax and regular tax). Carbon tax rate of outgoing product could be described as $CR^{mp} = CT/MP$. $MP = C_0+CT+RT+G$ is the product's mill price (output value), RT is the regular tax and G is the profit of outgoing product.

There usually was a fluctuation range for carbon tax, and the lower limit was take for simplicity. Suppose that the positive and negative increment of carbon tax are ΔCT and $-\Delta CT$, thus, $CT = [CT]\pm\Delta CT$. Introducing the positive and negative increment would contribute to control the carbon emissions for the enterprise itself. And it also is useful for the supervision department to monitor carbon emissions and to reward or punish the enterprise.

The formula for calculating carbon tax of a product was given as follows:

$$CT = \lambda_{CO_2} \cdot CE \quad (1)$$

where, CT is carbon tax, CE is carbon emissions (or carbon footprints), λ_{CO2} is convert coefficient. The convert coefficients were different in different countries, because their tasks to reduce carbon emissions were different. For the most countries and districts, such as Finland, Sweden, Italy and British Columbia, Canada, the convert coefficient was formulated uniquely according to carbon content of fossil energy. In some other countries, such as Norway, the convert coefficients were different in different industries and different fuels (Wang, 2010). The convert coefficient of carbon tax was set λ_{CO2} = 25USD/tCO_2, which was the carbon price being recommended for manufacturers in G20 countries (Max, 2011).

Carbon footprints calculation: carbon emissions (carbon footprints) of product are from 3 stages: (a) material→enterprise, (b) design and manufacture, (c) use→garbage collection. Carbon emissions in stage (a), (b), (c) construct the carbon emissions of full life circle, carbon emissions in stage (a), (b) are the emphasis in this study.

A significant basic work in low-carbon product design is to calculate carbon footprints. Previous researches on carbon emissions mainly focused on economy, management and public behavior, for example, low-carbon economy in the economics, green supply chain, and carbon emissions trade and carbon footprints calculation in the management science (IPCC, 2006). Those researches mentioned above weighted heavily toward supporting for studying carbon emissions in economy and management, it is also helpful to calculate carbon emissions for product low-carbon design. Those research achievements provide support for calculating carbon emissions; however, the precise extent of calculation and detailed data accumulation are still poor, and that restricts the development of the research about low-carbon product design. These are the issues remaining to resolve.

For calculating carbon footprints in low-carbon product design, the following approaches are worth watching: (a) Generic Bill of Materials (GBOM) (Song and Lee, 2010), (b) LCA database (EC and JRC, 2010), (c) Test and calculation approach, (d) Connection characteristics analysis method (Zhang *et al*., 2012), (e) Activity-based carbon-computing method (Tang *et al*., 2011), (f) PAS 2050 (British Standards Institute, 2008), (g) Contrast and estimation approach. Due to the complexity of method (a)~(f), method (g) was employed in this study. This method tested the typical parts to get its equivalent electricity energy consumption, then converted the equivalent electricity energy consumption into carbon emissions and carbon tax. The engineer with production experience contrasted the parts of product with the typical parts and estimated roughly calculated its energy consumption, then the carbon emissions and carbon tax were obtained.

LOW-CARBON PRODUCT OPTIMIZATION DESIGN MODEL

Low-carbon product optimization design model with performance, cost and carbon tax as design objectives was built to cope with the coupling or conflict relation among the three objectives. NSGA-II was employed to find the Pareto optimal set.

Mass customization configuration design or modular design was studied in this study. Product's function modules were classified into three categories (Wei *et al*., 2007): (a) Core module, (b) Accessory module, (c) Optional module. Each module category M_i was composed of module series M_{ij}, which was composed of modular entities M_{ijk}, where, i = 1, 2, 3; j = 1, 2, ... , J; k = 1, 2,..., K. The optimization objectives of low-carbon product optimization design in enterprise are performance P, basis cost C_0 and carbon tax CT. For providing invariable basis data, this study set C = C_0+CT+RT, where, C_0 is basis cost, CT is carbon tax, RT is regular tax. The multi-objective optimization problem can be described by Eq. 2:

$$\begin{gathered}\text{Minimize } \psi = \{P^{-1}, C_0, CT\} \\ \text{Subject to } [P] - P \le 0,\ C_0 - [C_0] \le 0,\ CT - [CT] \le 0\end{gathered} \quad (2)$$

where, $C_0 = C_0^{mod} + C_0^{asse} + C_0^{tran}$, C_0^{mod}, is total basis cost of modules, C_0^{asse} is total basis cost of assemble, C_0^{tran} is total basis cost of transportation, [P] is the lowest performance of a product, [C_0] is the highest basis cost of a product, [CT] is the highest carbon tax of a product.

This study developed the former equations (Wei *et al*., 2007), established the low-carbon product optimization design models driven by performance P, basis cost C_0 and carbon tax CT as follows:

Low-carbon product optimization design model driven by performance:

$$\text{Maximize } P=\sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}x_{ijk}\sum_{d=1}^{D}\omega_d\gamma_{ijk,d} \quad (3)$$
$$\text{Subject to } [P]-P\le 0$$

where, $P = \{p_d|d = 1, 2, ..., D\}$ is the evaluation index set of product performance. x_{ijk} is a binary decision variable denoting whether M_{ijk} is configured in a product, '0' denotes 'NO' and '1' denotes 'YES'. d denotes some performance of a product, the higher the P_d is, the better the dth performance is. ω_d is the weight vector. $\gamma_{ijk,d}$ is the degree that M_{ijk} contributes to P_d. The quantized value of $\gamma_{ijk,d}$ could be evaluated using fuzzy set: namely, strong, less strong, medium, weak or irrelevant. And the corresponding fuzzy values are 9, 7, 4, 1 and 0, respectively.

Low-carbon product optimization design model driven by basis cost:

$$\text{Minimize } C_0=\sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}x_{ijk}c_{0ijk} \quad (4)$$
$$\text{Subject to } C_0-[C_0]\le 0,\ (1+\eta)C\le C_{max}$$

where, c_{0ijk} is the basis cost of M_{ijk} (including the cost of raw material, cold working and hot working and modules assemble). $\eta = G/C$ is profit rate of enterprise, G is after-tax profit, $C = C_0+CT+RT$ is after-tax cost of outgoing product, C_{max} is the highest cost that customers could afford. For the sake of simplicity, the basis cost of transportation C_0^{tran} was leaved aside in this study.

Low-carbon product optimization design model driven by carbon tax:

$$\text{Minimize } CT=\lambda_{CO_2}\sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}x_{ijk}\cdot CE_{ijk} \quad (5)$$
$$\text{Subject to } CT-[CT]\le 0$$

where, CE_{ijk} is carbon emissions of M_{ijk} (including carbon emissions of raw material, cold working and hot working and modules assemble). For the sake of simplicity, the carbon emissions of transportation CE^{tran} was leaved aside in this study.

Equation 3-5 construct a multi-objective optimization problem with 3 optimization objectives. Note that Eq. 4 and 5 could be replaced by Eq. 6, because $C_{CT} = C_0+CT$. Then the original problem is equivalent to a problem constitutive of Eq. 3 and 6. This is a optimization problem with 2 optimization objectives:

$$\text{Minimize } C_{CT}=\sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}x_{ijk}(c_{0ijk}+\lambda_{CO_2}\cdot CE_{ijk}) \quad (6)$$
$$\text{Subject to } C_0-[C_0]\le 0,\ CT-[CT]\le 0$$

Constraint of configuration design: To assemble a product, only one module entity M_{ijk} should be selected among one module series M_{ij}. The constraint could be described by Eq. 7:

$$\text{Maximize } \left\{\sum_{k=1}^{K}x_{ijk}\right\}=1,\ i=1,2,3,\ j=1,2,\dots,J \quad (7)$$

Note: The performance-driven model Eq. 3 and cost-driven model Eq. 4 were developed based on the traditional design models driven by performance and cost (Wei *et al*., 2007). There were 3 differences between the models in this study and the traditional ones, (a) Incorporating carbon tax system into low-carbon product design to build the low-carbon product optimization design model, (b) Considering the carbon emissions and corresponding carbon tax of raw material, cold and hot processing and modules assemble, (c) Incorporating the carbon tax into the basis cost C_0 of product, the original problem could be regarded as a multi-objective optimization problem with C_{CT} and P as optimization objectives.

The optimization design flow chart of a low-carbon product was shown in Fig. 1.

CASE STUDY

The configuration optimization design of touring bicycle was studied in this study. The problem is to select modules in module set U to structure a complete bicycle, meanwhile, the bicycle should satisfy the requirements of performance, cost and carbon tax. The module set U was given in Table 1, the mainly parts list was shown in Table 2, the value $\gamma_{ijk,d}$ in Table 3 denotes the degree that M_{ijk} contributes to P_d.

Basis data: The basis cost c_{0ijk} in Table 1 was provided by a bicycle factory. The carbon emissions CE_{ijk} was estimated by veteran engineer based on GBOM. The equivalent electricity consumption was first estimated according to the material, process and device, man-hour etc., meanwhile, analogy was used as well. Then the equivalent electricity consumption was converted into carbon emissions CE_{ijk}.

This study only considered 6 performances of touring bicycle: weight, strength, lifetime, flexibility, comfort, modeling. The correlation degree $\gamma_{ijk,d}$ was

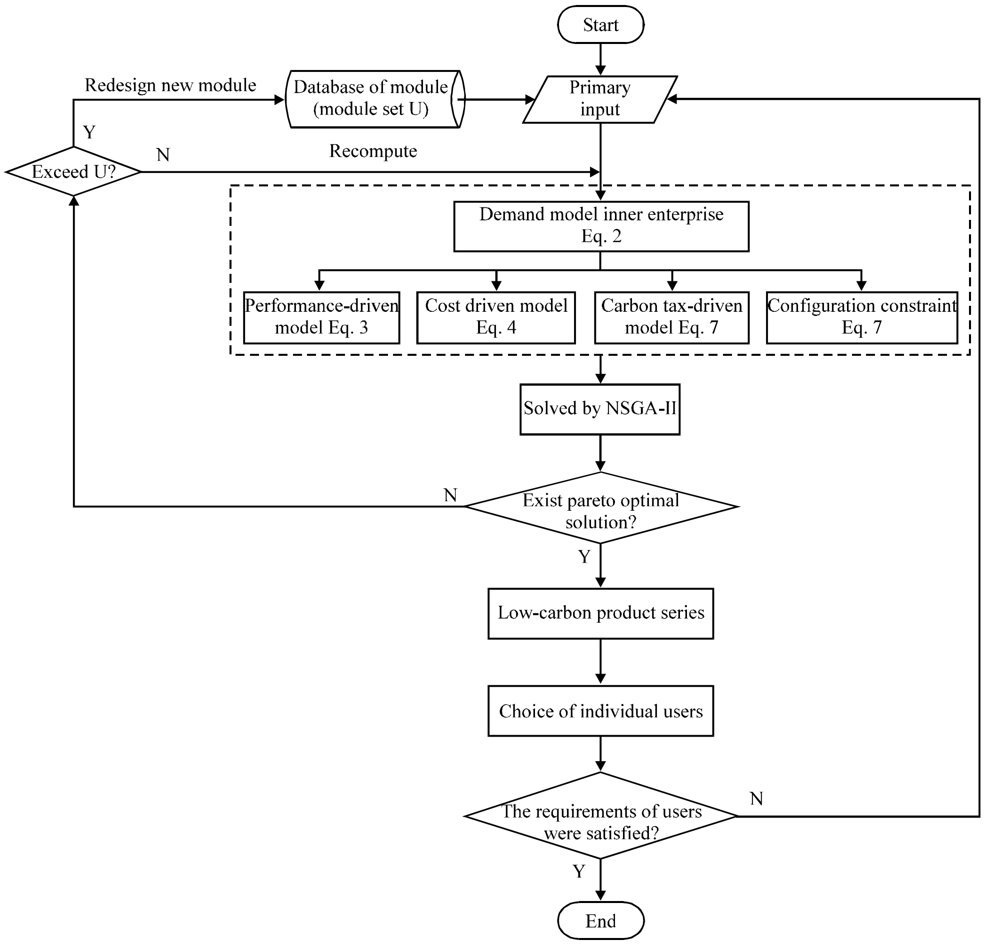

Fig. 1: Optimization design flow chart of a low-carbon product

Table 1: Module series, module entity and its affiliated parts in product family of touring bicycle

Module series	Module entity	Affiliated parts	c_{0ijk}/USD	CE_{ijk}/Kg	Module type
Execution module	M_{111}	12, 15	19.4	24.3	☆
	M_{112}	13, 16	28.4	31.2	☆
	M_{113}	14, 15	53.5	25.7	☆
	M_{114}	12, 16	17.4	36.4	☆
	M_{115}	13, 15	30.3	19.8	☆
	M_{116}	14, 16	51.6	23.5	☆
Powertrain module	M_{121}	6, 8, 10, 11	14.5	15.4	☆
	M_{122}	6, 9, 10, 11	18.2	12.3	☆
	M_{123}	7, 8, 10, 11	10.8	21.5	☆
	M_{124}	7, 9, 10, 11	14.5	20.6	☆
Supporting module	M_{131}	20, 25, 28, 29	97.2	32.0	☆
	M_{132}	21, 24, 26, 29	82.4	45.3	☆
	M_{133}	22, 23, 27, 29	34.3	23.7	☆
Braking module	M_{141}	1, 2, 3	6.0	10.4	☆
	M_{142}	1, 2, 4	12.8	21.1	☆
	M_{143}	1, 2, 5	7.6	13.5	☆
Speed changing module	M_{151}	17	11.4	20.2	☆
	M_{152}	18	13.2	17.6	☆
	M_{153}	19	8.0	30.1	☆
Accessory module	M_{211}	30, 31, 33, 35, 36, 38, 40	8.8	25.6	Δ
	M_{212}	30, 32, 33, 34, 37, 39, 40	13.9	31.4	Δ
Optional module	M_{311}	43, 45	1.9	14.9	○
	M_{312}	41, 43, 45	2.7	22.4	○
	M_{313}	41, 42, 43, 44, 45	4.6	43.4	○

(a) ☆ denotes core module, Δ denotes accessory module, ○ denotes optional module. (b) c_{0ijk} was provided by a bicycle factory, CE_{ijk} was estimated by veteran engineer based on GBOM

Table 2: Main parts in product family of a touring bicycle

SN	Name	SN	Name	SN	Name	SN	Name
1	Brake levers	13	Wheels 2	25	Front fork 3	37	Handlebar grips 2
2	Brake cables	14	Wheels 3	26	Handlebar 1	38	Mud-guards 1
3	Caliper brakes	15	Tyres 1	27	Handlebar 2	39	Mud-guards 2
4	Disc brakes	16	Tyres 2	28	Handlebar 3	40	Reflector
5	Band-type brakes	17	Transmission 1	29	Seat pillar	41	Water bottle cages
6	Bike pedals 1	18	Transmission 2	30	Bike stand	42	Basket
7	Bike pedals 2	19	Transmission 3	31	Saddle 1	43	Inflator
8	Chainwheel and crank 1	20	Bike frame 1	32	Saddle 2	44	Luggage carrier
9	Chainwheel and crank 2	21	Bike frame 2	33	Safety helmet	45	Safety lock
10	Cycle chain	22	Bike frame 3	34	Bell 1		
11	Flywheel	23	Front fork 1	35	Bell 2		
12	Wheels 1	24	Front fork 2	36	Handlebar grips 1		

Table 3: Correlation degree that a module entity M_{ijk} contributes to performance P_d

	P_1	P_2	P_3	P_4	P_5	P_6		P_1	P_2	P_3	P_4	P_5	P_6		P_1	P_2	P_3	P_4	P_5	P_6
M_{111}	4	1	4	4	1	7	M_{123}	1	4	7	4	4	7	M_{151}	4	7	7	9	4	9
M_{112}	7	4	4	1	1	4	M_{124}	4	4	7	7	7	4	M_{152}	7	9	9	9	7	9
M_{113}	9	9	7	4	1	9	M_{131}	9	9	7	7	9	9	M_{153}	4	4	7	7	4	7
M_{114}	4	1	1	4	1	4	M_{132}	4	7	7	4	7	9	M_{211}	7	4	4	1	9	4
M_{115}	4	4	7	1	1	7	M_{133}	7	4	4	4	4	7	M_{212}	4	7	4	1	7	7
M_{116}	9	7	9	4	1	7	M_{141}	4	7	4	7	7	9	M_{311}	9	4	7	1	4	7
M_{121}	4	7	7	4	7	7	M_{142}	7	9	7	9	9	7	M_{312}	7	4	7	1	7	9
M_{122}	7	9	7	7	9	9	M_{143}	1	7	4	7	4	7	M_{313}	4	4	7	1	9	7

The data in the table was obtained by fuzzy evaluation

Table 4: 13 detail low-carbon touring bicycle configuration design schemes found by NSGA-II

Configuration scheme	P	C_0 (USD)	CE (Kg)	CT (USD)	C_{CT} (USD)	CT/C_0(%)	V_{in} (USD)	C (USD)	P/C (%)
M_{112} M_{122} M_{133} M_{142} M_{152} M_{212} M_{312}	42.24	123.5	159.7	3.99	127.5	3.23	170.21	142.80	29.58
M_{112} M_{122} M_{133} M_{142} M_{152} M_{212} M_{313}	42.39	125.4	180.7	4.52	129.9	3.60	173.46	145.52	29.13
M_{115} M_{122} M_{133} M_{142} M_{152} M_{212} M_{313}	42.48	127.3	169.3	4.23	131.5	3.32	175.58	147.30	28.84
M_{113} M_{122} M_{133} M_{141} M_{152} M_{211} M_{312}	42.77	136.7	137.7	3.44	140.1	2.52	187.09	156.95	27.25
M_{113} M_{122} M_{133} M_{141} M_{152} M_{211} M_{313}	42.91	138.6	158.7	3.97	142.6	2.86	190.29	159.64	26.88
M_{116} M_{122} M_{133} M_{142} M_{152} M_{211} M_{311}	43.19	140.8	138.7	3.47	144.3	2.46	192.60	161.58	26.73
M_{116} M_{122} M_{133} M_{142} M_{152} M_{211} M_{312}	43.75	141.6	146.2	3.66	145.3	2.58	193.94	162.70	26.89
M_{113} M_{122} M_{133} M_{142} M_{152} M_{211} M_{311}	44.10	142.7	140.9	3.52	146.2	2.47	195.20	163.76	26.93
M_{113} M_{122} M_{133} M_{142} M_{152} M_{211} M_{312}	44.66	143.5	148.4	3.71	147.2	2.59	196.51	164.86	27.09
M_{113} M_{122} M_{133} M_{142} M_{152} M_{211} M_{313}	44.81	145.4	169.4	4.24	149.6	2.91	199.75	167.58	26.74
M_{113} M_{122} M_{133} M_{142} M_{152} M_{212} M_{311}	45.06	147.8	146.7	3.67	151.5	2.48	202.23	169.65	26.56
M_{113} M_{122} M_{133} M_{142} M_{152} M_{212} M_{312}	45.62	148.6	154.2	3.86	152.5	2.59	203.59	170.80	26.71
M_{113} M_{122} M_{133} M_{142} M_{152} M_{212} M_{312}	45.76	150.5	175.2	4.38	154.9	2.91	206.77	173.46	26.38

(a) The carbon emissions of transportation CE^{tran} and corresponding carbon tax CT^{tran} were leaved aside in this study. (b) Series number 8-10 were the schemes meeting individual demands of C≤168 USD, P≤44 and P/C≥26%

denoted by relative measurement degree (9, 7, 4, 1, 0), then the correlation degree matrix was constructed as shown in Table 3. The weight vector ω of touring bicycle performance p_d (d =1, 2, ..., 6) was obtained by hierarchy analysis method (Saaty, 1980).

$$\omega = \{ 0.0450, 0.4419, 0.0298, 0.2524, 0.1860, 0.0449 \}$$

The design specifications: The minimum profit rate $\eta = (G/C_{in}) = 16\%$, C_{in} is the ex-factory price of the product. The maximum price C_{max} = 210 USD, the minimum performance [P] = 42, the minimum performance cost ration [P/C]= 25%, the maximum carbon tax rate of basic cost [CR] = $[CT/C_0]$ = 3%, the regular tax RT = 12% C_0, (a) Find the product series of touring bicycle that satisfy the requirements of performance, cost (profit) and carbon tax; (b) Find configuration design schemes meeting individual requirements C≤168 USD, P≤44 and P/C≥26%.

Experiments settings: NSGA-II was employed to solve this problem. Set iteration times δ = 250, population size N = 100, crossover probability P_c = 0.9, mutation probability P_m = 0.1.

The Pareto optimal solution set was obtained as shown in Table 4.

RESULT ANALYSIS AND DISCUSSION

(1) The Pareto optimal solution set of low-carbon touring bicycle was shown in Table 4. C and other data could be derived from C_{CT}, CT, such as basis cost $C_0 = C_{CT}$-CT, ex-factory price $C_{in} = C_0+C_{CT}$+RT+G, G = 22% C_0, market price $C_{mark} = C_{in}+\Delta V$, ΔV = 7.5% C_0. The Pareto set mentioned above met the requirements of performance, cost (profit) and carbon tax. (2) There were 3 design schemes in Table 4 that met the individual requirement of users, the requirements are C≤168 USD,

$P \le 44$ and $P/C \ge 26\%$. The design schemes were (a) C = 163.76 USD, P = 44.10, P/C = 26.93%; (b) C = 164.86 USD, P = 44.66, P/C = 27.09%; (c) C = 167.58 USD, P = 44.81, P/C = 26.74%. The detailed configuration schemes were shown in shadow in Table 4. Parenthetically, the CR^{C0} of the 3 schemes were 2.47, 2.59 and 2.91%, respectively. It follows that the 3 schemes met the requirements of users and enterprise simultaneously.

CONCLUSION

Carbon tax system is an effective mechanism to monitor and control the carbon emissions from enterprise. This study introduced carbon tax into product design, and presented a low-carbon product optimization design method satisfying the requirements of performance, cost and carbon tax. It will be inevitable to influence the coupling between performance and cost of product. That is to enhance the cost and lower the performance cost ratio. How to find the equilibrium solutions on the premise of meeting the requirement of carbon tax could be regarded as a multi-objective problem.

With the product configuration design as background, this study built low-carbon product multi-objective (performance, cost and carbon tax) optimization models. These models yet could be converted to multi-objective optimization models driven by cost including constraints of allowable carbon tax and performance. NSGA-II was employed to find Pareto optimal solution set that met the requirements of performance, cost and carbon tax. Then the wanted product design schemes could be selected from the solution set mentioned above according to the individual requirements of users. A case of low-carbon configuration optimization design for touring bicycle was studied in this study. The result showed that the design schemes found by the method proposed could simultaneously meet both the requirements of enterprise and the individual requirements of users. This study could provide a reference for enterprise to conduct low-carbon product configuration design.

Carbon emissions (carbon tax) calculation is the basis of low-carbon product design for the enterprise. Though the carbon emissions (carbon tax) calculation in this study was simple, it was much rough. A simple and accurate method to calculate carbon emissions (carbon tax) is scarce. The problems need to be further studied.

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