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Accelerating preliminary low-carbon design for products by integrating TRIZ and Extenics methods

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Abstract

Low-carbon performance as well as the quality and cost of a new product are normally emphasized in the early phase of low-carbon design for products. Although the TRIZ method and Extenics theory can be applied separately to solve contradiction problems in design field, these two methods have their weaknesses in applications. The purpose of this study is to provide a novel model for accelerating the preliminary low-carbon design by integrating the TRIZ and Extenics methods. Analysis tools and knowledge base tools of TRIZ are adopted to generate generic strategies; basic-element theory and dependent function of Extenics are used to qualitatively and quantitatively describe the conflict problem in a formalized model, and detailed transformation operations are employed to achieve the feasible design solutions. Innovative design schemes for two kinds of conflict problems of the screw air compressor demonstrate the effectiveness of the proposed method.

Keywords

Low-carbon design, TRIZ, Extenics, conflict problem model, conflict resolution

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Introduction

Since the industrial revolution, especially the development of large-scale manufacturing technology, people can access to manufacturing products at low cost. However, the conventional methodologies for product design and manufacturing neglect the environmental factors, which result in the depletion of natural resources and the deterioration of the environment. Environmentally conscious design or economics and ecology design, eco-design, not only focuses on the products' quality and cost but also takes into account the environment factors of products in entire life cycle.[1,2] Eco-design has attracted a heated research in both academia and industry. Kobayashi[3,4] proposes the evolution strategy of a product, life-cycle planning (LCP) methodology, and integrates the quality, cost, and environmental aspects in the eco-design under the LCP framework to enhance the eco-effectiveness of a product. Knight and Jenkins[5] establish a compatible suite of tools in eco-design, the checklists, guidelines, and a material, energy and toxicity matrix, to identify key environmental aspects of a product in life cycle. Tyl et al.[6] takes a comparative study on ideation mechanisms during early phase of eco-design. Cluzel et al.[7] introduce the eco-

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innovation methodologies and tools to complex systems industries, in which the eco-innovation design demands are highly specific.

Research branches of eco-design are also significantly concerned during its development, low-carbon design,[8] green design,[9,10] and sustainable design.[11,12] In this article, we focus on the low-carbon design for products. Methodology of low-carbon design for products considers the quality, cost, and the carbon footprint or carbon emission of products lifetime, and it mainly encompasses three research aspects: low-carbon product design, evaluation of carbon footprint, and low-carbon product optimization.[13,14]

Song and Lee[15] develop a low-carbon design system for products, and it can calculate the greenhouse gas (GHG) emissions of each part and establish the bill of materials (BOM) structure, identify the problematic parts, and evaluate the GHG emission of newly designed products. Qi and Wu[16] integrate low-carbon technologies and modular design strategy to construct the dynamic configuration application model. He et al.[14] propose a design solution model to search the lowest carbon footprint scheme by means of the mapping between design solution space and decision space. Evaluation of carbon emission is the research foundation of low-carbon design. Zhang et al.[17] propose an effective way of calculating carbon footprint based on the connection characteristics and develop a model to identify connection units with high carbon emission, which benefits modification of connection units and reuse of the carbon footprint data and knowledge. Sun et al.[18] establish the production process–oriented basic carbon footprint base through tracking carbon footprint of each part and construct the carbon footprint hierarchical model of complex equipment by means of drawing the information of carbon footprint layer by layer. Branker et al.[19] propose a machining microeconomic model used to evaluate machining parameters, carbon emission and other environmental costs based on the life-cycle analysis methodology. For low-carbon design optimization, Kuo and colleagues[20,21] construct a collaborative framework to collect and calculate carbon emission of products for enterprises and establish a low-carbon optimal evaluation model by multi-objective planning. Chu et al.[22] propose a computer-aided design (CAD)-based approach that allows to change combination of parts, select assembly method, and rearrange assembly sequence, then integrate genetic algorithm method to produce an optimal structure from the design alternatives. Xu et al.[13] adopt non-dominated sorting genetic algorithm to solve the multi-objective optimization problem in low-carbon design for meeting triple requirements of user, enterprise, and government.

In our work, we focus on the preliminary low-carbon design for products to coordinate the conflict problems in lifetime. Case-based reasoning (CBR) method is widely used in the field of products design;[23,24] it stores the prior design knowledge in a product case rather than constructing complex rules, thus designers can effectively reuse the past knowledge and revise the problematic parts to generate a newly designed product.[25–27] Despite the ability of CBR to achieve routine design, the level of proposed solutions typically belongs to incremental innovation design.[28] In the field of low-carbon design, the conflict problem involves the quality, cost, and carbon footprint, and these three factors are coupled in products lifetime. On this condition, CBR is incompetent; it needs a method to devise a solution with a high level of innovation by increasing new knowledge from other technical domains. TRIZ (Theory of Inventive Problem Solving, a Russian acronym) is an effective method to provide solutions with generic knowledge from all kinds of fields.[29] In TRIZ method, the analysis tools include contradiction matrix, substance field analysis, and ARIZ (Algorithm of Inventive Problem Solving); the knowledge base tools consist of 40 inventive principles and 76 standard solutions.[30,31] Designers use these tools to develop the resolution strategies for technical contradiction and physical contradiction.

Yang and Chen[28] integrate TRIZ and CBR method to solve the eco-innovation, use previous cases to satisfy functional performances, and employ inventive principles and evolution patterns of TRIZ to enhance the design level of innovation. Chou[32] proposes an ARIZ-based life-cycle engineering (LCE) model, with a new product structure and an effective assessment method, for implementing eco-design of products. Vidal et al.[33] propose an innovative methodology that integrates fuzzy cognitive maps and TRIZ evolution strategies to assist designers in predicting technological evolutions in ceramic industry for more environmentally friendly products.

With analysis tools and knowledge base tools, TRIZ method can provide generic design knowledge; however, it lacks the detailed transformation operations during transforming the generic solution to specific solution, and in TRIZ method, representation for contradiction problem in a qualitative and quantitative framework, which is essential to reveal the transformation mechanism for contradiction problem solving, is also absent. Extenics is a new methodology used to solve the antithetical problem and incompatible problem, and it belongs to the operation research and artificial intelligence field.[34] In Extenics,[35] it adopts the basic-element theory, including matter-element, affair-element, and relation-element, to represent the conflict problem in a formalized model; uses the dependent function to quantitatively identify and evaluate the conflict problem; and employs detailed transformation operations to transform the generic strategies into the feasible design scheme. Zhao et al.[36] propose the conflict solution for product performance requirements based on propagation analysis in Extenics; improve the retrieval method to get similar cases, implement transformation operations on the similar cases by propagation analysis, and evaluate the effect and level of propagation to achieve the optimal scheme. Tang et al.[37] integrate extension transformations and gene expression programming (GEP) for incompatible problems and overcome the combination explosion of schemes. Chen et al.[38] introduce the transformation bridge method in Extenics to solve the conflict problem between new additional green characteristics and original product performance in green design. However, in Extenics, it is difficult for designers to generate original generic strategies.

Considering the similarity of contradiction problem or conflict problem in TRIZ and Extenics discussed in discussion section, and their advantages and disadvantages, this work focuses on accelerating preliminary low-carbon design for products by integrating the approaches of TRIZ and Exteincs. The rest of this article is organized as follows. The methodology of TRIZ and Extenics in solving the contradiction or conflict problem, respectively, is introduced. The representation model of conflict problem for similar cases is established. The proposed method that integrates TRIZ and Extenics to achieve low-carbon design is presented. Next section demonstrates the effectiveness of the proposed method by a case study in solving technical contradiction or antithetical problem of noise and physical contradiction or incompatible problem of carbon footprint for the screw air compressor. Discussion is given, and conclusion is finally drawn along with the recommendation for future research.

TRIZ

Pioneered by Altshuller, TRIZ method offers an extensive series of problem analysis tools and knowledge base tools and is widely used to more easily solve inventive problems. Chechurin and Borgianni[39] review the top cited publications of TRIZ to make designers understand its applications. Ben Moussa et al.[40] review the use of TRIZ in green supply chain problems. Petkovic et al.[41,42] apply TRIZ creativity enhancement approach to get creative conceptual design ideas for robotic gripper and joint. Lin et al.[43] adopt the TRIZ innovative method to improve short circuit devices. TRIZ method is considered a critical tool in cleaner production, especially in chemical engineering, to minimize industrial waste and emissions by means of enhancing the efficiency of the use of energy and materials.[44,45] In recent decades, TRIZ method is also integrated with other approaches in product design and development, quality function deployment (QFD) and TRIZ,[4,46] life-cycle assessment (LCA) and TRIZ,[47,48] and CBR and TRIZ;[49,50] the purpose of these integration methods is to promote the innovation level in inventive problem solving.

The definition of technical contradiction and physical contradiction in TRIZ, and the corresponding solving tools used in this work, referred to as contradiction matrix, 40 inventive principles, and separation method, are introduced below.

Technical contradiction and physical contradiction

Contradiction problems often occur in engineering, a technical contradiction arises when efforts to improve one system characteristic but degrade another one. For instance, in preliminary design for the screw air compressor, designers want to set a high-power motor to enhance work efficiency, but the high-power motor contributes to higher energy consumption. Thus, the improved characteristic is work efficiency and the degraded characteristic is energy consumption.

A physical contradiction involves one characteristic in a system with two opposite requirements. For instance, with the same example, designers require the rotational speed of dual screw rotors to be fast to increase the air input and require the speed to be slow to decrease energy consumption, thus rotational speed of dual screw rotors is the characteristic that results in a physical contradiction.

Technical contradiction and physical contradiction can be transformed seen from the above same example. The technical contradiction is more easily to find with its two obvious characteristics, such as the work efficiency and the energy consumption. The physical contradiction is a deeper conflict problem with its unobvious characteristic, such as the speed of dual screw rotors.

Tools for inventive problem solving

In TRIZ method, a technical contradiction can be solved using the contradiction matrix. Altshuller examined more than 100,000 patents to reveal 39 engineering characteristics and 40 inventive principles and constructed the contradiction matrix table (Table 1). There are two steps to solve the technical contradiction. Step 1 analyzes the attributes of the problem and extracts the improved characteristic in the column and the degraded characteristic in the row as in the contradiction matrix table. Step 2 attempts to solve the contradiction using the recommended inventive principles that are listed in the intersection cell.

In modern TRIZ, researchers summarized four basic separation methods to solve the physical contradiction; they are *Separate in Time, Separate in Space, Separate on Condition*, and *Separate by System*. Each type of

Table 1. Part of the contradiction matrix table.[51]

Improve this one without making this one worse		Weight of moving object	Weight of stationary object	Length of moving object	...	Volume of stationary object	Speed	Force	...
		1	2	3	...	8	9	10	...
1	Weight of moving object		–	15 8 29 34	...	–	2 8 15 38	8 10 18 37	...
2	Weight of Stationary object	–		–	...	5 35 14 2	–	8 10 19 35	...
3	Length of moving object	8 15 29 34	–		...	–	13 4 8	17 10 4	...
...	...	...	...	...	...	...	...	...	...
30	Object-affected harmful factors	22 21 27 39	2 22 13 24	17 1 39 4	...	34 39 19 27	21 22 35 28	13 35 39 18	...
31	Object-generated harmful factors	19 22 15 39	35 22 1 39	17 15 16 22	...	30 18 35 4	35 28 3 23	35 28 1 40	...
32	Ease of manufacture	28 29 15 16	1 27 36 13	1 29 13 17	...	35	35 13 8 1	35 12	...
...	...	...	...	...	...	...	...	...	...

Suggestions for inventive Principle 3:
A: change an object's structure from uniform to non-uniform;
B: change an action or an external environment from uniform to non-uniform;
C: make each part of an object function in conditions most suitable for its operation;
D: make each part of an object fulfill a different useful function.

Solving technical contradiction by contradiction matrix; inventive principles suggest approaches of improving one attribute without making the other one worse.
The matrix table offers inventive principles for the intersection $M_{Y31\text{-}Y9}$: 35, 28, 3, 23:
35—transform physical/chemical state
28—replace mechanical system
3—local quality 23—feedback

Table 2. The four separation methods.[51]

Separation methods	Description	Suggested inventive principles
Separate in Time	One solution at one time, the opposite solution at another	1, 7, 9, 10, 11, 15, 16, 18, 19, 21, 24, 26, 27, 29, 34, 37
Separate in Space	One solution in one place, the opposite solution at another	1, 2, 3, 4, 7, 13, 14, 17, 24, 26, 30, 40
Separate on Condition	One solution for one element, the opposite for another	28, 29, 31, 32, 35, 36, 38, 39
Separate by System	Sub-system, super-system	5, 6, 12, 22, 33, 40, 1, 3, 24, 27
	Switch to inverse system	13
	Switch to another system	6, 8, 22, 27, 25, 40

separation method involves relevant inventive principles (Table 2).

Extenics

In the Extenics method, it also has its specific model for conflict problems and solving strategies. Ma et al.[52] apply the Extenics theory in mass customization production, construct the matter model of the complex design system, and achieve redesign for products based on requirements by transforming the matter model. Zhao et al.[53] propose a retrieval method for similar cases based on Extenics theory and employ it into the product configuration design. Chao and Li[54] propose the intelligent maximum power point tracking (MPPT) algorithm based on Extenics theory, which helps automatically adjust the step size to track the photovoltaic array maximum power point (MPP). Ye[55] applies Extenics method in the misfire fault diagnosis of gasoline engines. Researchers also integrate the Extenics method with intelligent algorithms for its wider application, Extencis and neural network[56,57] and Extenics and genetic algorithm.[58,59]

In this section, we briefly introduce the conflict problems, namely, incompatible problem and antithetical problem represented in extension model, and the transformation operations for the conflict problem solving.

Incompatible problem and antithetical problem in Extenics

Extension model represents an incompatible problem with basic-element theory as following form[35]

$$P = g * l \tag{1}$$

$$g = (Z_g, c_s, c_s(Z_g)), \quad l = (Z_l, c_t, c_t(Z_l))$$

where symbol "*" denotes correlation, and incompatible problem (P) is related to the design goals (g) and the current conditions (l). Representing g and l in the basic-element model, Z_g is the object of the goal, c_s is the characteristic required when g is achieved, $v_s = c_s(Z_g)$ is the value or range of Z_g about c_s, Z_l is the object of condition, c_t is the characteristic of the current condition, and $v_t = c_t(Z_l)$ is the value or range of Z_l about c_t.

Here, we use dependent function $k(g, l)$ to quantitatively evaluate the incompatible extent of each characteristic for the problem p. The evaluation rule is described in equation (2)

$$\begin{cases} k(g, l) \geq 0, & c_t(Z_l) \in c_s(Z_g) \\ k(g, l) < 0, & c_t(Z_l) \notin c_s(Z_g) \end{cases} \tag{2}$$

In the equation, it reveals that when $k(g, l) < 0$, the condition characteristic c_t is not satisfied with the requirement (the goal), thus it contributes to an incompatible problem.

In Extenics method, antithetical problem involves two parameters, the two characteristics requirements cannot be satisfied simultaneously under current condition, and the antithetical problem is expressed as

$$P = (g_1 \wedge g_2) * l \tag{3}$$

and the coordination work is to make $k(g_1, l) > 0$ and $k(g_2, l) > 0$.

Dependent function, the evaluation tool for conflict problems

Suppose x is any point in real axis and $X_0 = [a, b]$ is any interval in real field, we call

$$\rho(x, X_0) = \left| x - \frac{a+b}{2} \right| - \frac{b-a}{2} \tag{4}$$

the extension distance between point x and interval X_0; suppose another interval $X = [c, d]$, $X_0 \subset X$, then dependent function can be expressed as

$$k(x) = \frac{\rho(x, X)}{\rho(x, X) - \rho(x, X_0)} \tag{5}$$

Dependent function meets the following conditions:

1. when $x \in X_0$, $k(x) \geq 1$, and when $x = a$, $x = b$, and $k(x) = 1$;
2. when $x \in X - X_0$, $0 \leq k(x) < 1$, and when $x = c$, $x = d$, and $k(x) = 0$;
3. when $x \notin X$, $k(x) < 0$.

In design process, we redefine X_0 as the desirable interval and X as the acceptable interval. When design parameter x falls out of X, then $k(x) < 0$, namely, there is a contradiction problem.

For equations (4) and (5), there is a premise that the optimal point is at the middle of interval X_0. However, the optimal point is usually at the left to the middle point that the performance value is the smaller the better, or it is at the right to the middle point that the performance value is the larger the better. Thus, equations (4) and (5) are modified by side extension distance in Yang and Cai.[35]

Transformation operations for conflict problems

Transformation operations include substitution transformation, increasing transformation, expansion/contraction transformation, decomposition transformation, and duplication transformation. The transformed objects can be the conditions (l), the goals (g), and the dependent function (k). In design work, transformation for conditions is often used:

Substitution transformation (T_{Sub}). T_{Sub} uses one element (characteristic) to replace another one

$$T_{\text{Sub}} l_i = l_j \tag{6}$$

Increasing transformation (T_{Inc}). T_{Inc} increases one element (characteristic)

$$T_{\text{Inc}} l_i = l_i \oplus l_j \tag{7}$$

Expansion/contraction transformation ($T_{\text{Exp}}/T_{\text{Con}}$). $T_{\text{Exp}}/T_{\text{Con}}$ expands one element (characteristic value) or makes it contracted

$$\begin{cases} T_{\text{Exp}} l_i = \alpha l_i, & \alpha > 1 \\ T_{\text{Con}} l_i = \alpha l_i, & 0 < \alpha < 1 \end{cases} \tag{8}$$

Decomposition transformation (T_{Dec}). T_{Dec} decomposes one element into more detailed ones

$$T_{\text{Dec}} l = \{l_1, l_2, \ldots, l_n\} \tag{9}$$

Duplication transformation (T_{Dup}). T_{Dup}, here, denotes copying or reuse of the information of elements

$$T_{\text{Dup}} l_i = \{l_i, l_i*, l_i*, \ldots\} \tag{10}$$

In design process, using a single transformation is hard to solve the contradiction problem, thus the combination transformation is usually required.

Representation model of conflict problems

CBR method solves routine design problems by means of the operations: retrieval, reuse, revision, and retention. However, when the conflict problem is complex, especially in the low-carbon design that involves multiple factors, the CBR method is not competent. Thus, based on the CBR, we integrate TRIZ and Extenics to expand domain expert knowledge to achieve innovative low-carbon design. In this section, we construct the model of conflict problems of similar cases in CBR case base, including the representation and classification of cases, modeling of multi-factor conflict problems, and mapping operations of the conflict problem.

Representation and classification of similar cases

The representation of the product case Z^i in the design case base is

$$\{Z^i\} = \{Z^i | Z^i = (\text{Case\_Product}^i, C, V)\} \tag{11}$$

where $C = [\text{Pro\_Identity}^i, \text{Pro\_Name}^i, \ldots, \text{Pro\_Attribute}^i, \text{Pro\_Require}^i]^{\text{T}}$, $V = [v_1^i, v_2^i, \ldots, \{B^i_{\text{Pro\_Attribute}^i}\}, \{B^i_{\text{Pro\_Require}^i}\}]^{\text{T}}$, and Z^i denotes the ith product case. Case_Product^i, C, and V are the three elements. C represents the characteristics of a product, including identity number, name, attributes, and customer requirements. V represents the values of the characteristics in C.

By calculating dependent function value $k(PR^i, v(B^i_{\text{Pro\_Attribute}}))$ associated with the requirement PR^i and the characteristic value $v(B^i_{\text{Pro\_Attribute}})$, we can estimate which product cases can meet the customer demand. Then, we get the classifying result, called the *static classification*, as shown in Figure 1(a):

when $k(PR^i, v(B^i_{\text{Pro\_Attribute}})) > 0$, $Z^i \in V_+$;
when $k(PR^i, v(B^i_{\text{Pro\_Attribute}})) < 0$, $Z^i \in V_-$;
when $k(PR^i, v(B^i_{\text{Pro\_Attribute}})) = 0$, $Z^i \in V_0$.

However, when the dependent function value is changed because of transformation operations, the classifying result will be updated. We call this process *dynamic classification*, is shown in Figure 1(b). About this part content, we have researched the retrieval and classification method in Zhao et al.[60] In this work, we focus on the reuse, modification of existing similar cases knowledge, and inventive design.

In Figure 1(a), V_- represents a negative field, V_+ represents a positive field, and V_0 represents the critical

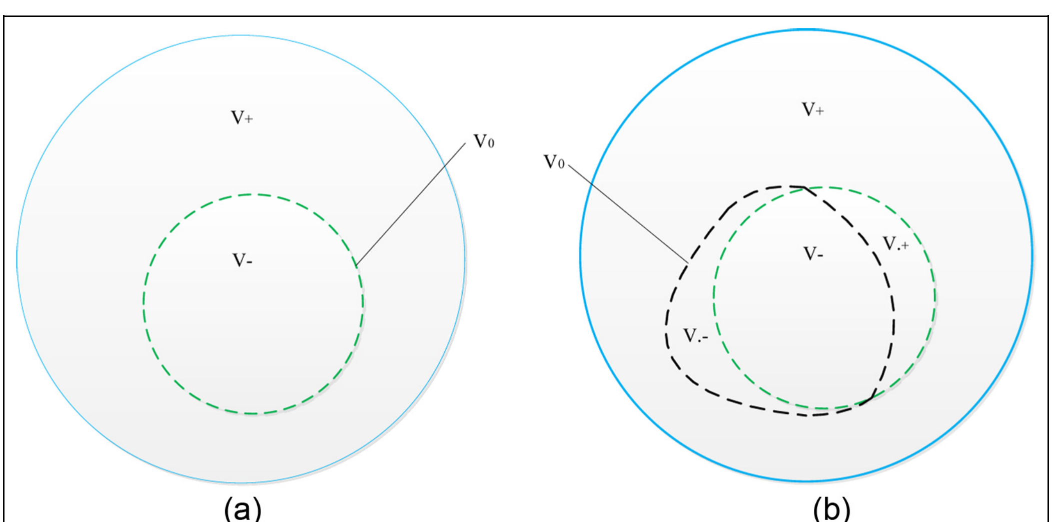

Figure 1. Classification states of product cases: (a) static classification and (b) dynamic classification.[60]

state. Figure 1(b) shows the dynamic classification states. Here, V_{-} represents the field of negative qualitative change, namely, the case from positive field to negative field; V_{+} represents the field of positive qualitative change, namely, the case from the negative field to the positive field.

Modeling of multi-factor conflict problems

In product case library, the cases in V_{+} or in V_{+} can be output directly after the static and dynamic classification; however, it is difficult to find a case that meets all characteristics in low-carbon design. Therefore, we choose the similar cases in V_{-} or V_{-} to achieve the objective by solving the unsatisfactory characteristics.

Suppose the number of characteristics (or attributes), $B^{i}_{\text{Pro\_Attribute}}$, is m_1 of a product case, number of requirement characteristics, PR^{j}, is m_2, $m_2 \leq m_1$; we define $B^{j}_{\text{Pro\_Attribute}}$ to be the characteristics in $B^{i}_{\text{Pro\_Attribute}}$ responding to that of PR^{j}; suppose there are n unsatisfactory characteristics, then conflict problem of a characteristic is expressed as

$$P_{j_1} = v(B^{j,j_1}_{\text{Pro\_Attribute}}) \uparrow v(PR^{j,j_1}) \tag{12}$$

In equation, $j = 1, 2, ..., m_2$; $j_1 = 1, 2, ..., n$; "$\uparrow$" denotes that the characteristic j_1 is not satisfied with the requirement j_1, namely, $k(PR^{j,j_1}, v(B^{j,j_1}_{\text{Pro\_Attribute}})) < 0$. Then, the conflict problem for a product case can be expressed as

$$P = \{P_1, \ldots, P_{j_1}, \ldots, P_n\} * Z^i \tag{13}$$

"*" denotes the correlation.

Mapping of conflict problems

Conflict problem model in equations (12) and (13) points out which characteristic is not satisfied, but it still needs to map the conflict problem of the unsatisfactory characteristic onto the basic structure to reveal its conflict mechanism. In this work, we adopt design matrix (DM) to describe the hierarchical relationships among the product characteristic, product module, structure, and low-carbon basic structure (LCBS). Here, LCBS refers to the basic structure unit, composed of three factors—carbon footprint, cost, and performance.

Construct design matrix (DM_1) for the required characteristics $c(B^{i}_{\text{Pro\_Attribute}})$, $i = 1, 2, ..., n$, and the design module M^j, $j = 1, 2, ..., m$, as follows

$$DM_1 = \begin{array}{c} \\ c(B^{1}_{\text{Pro\_Attribute}}) \\ \vdots \\ c(B^{n}_{\text{Pro\_Attribute}}) \end{array} \begin{array}{c} \begin{array}{ccc} M^1 & \cdots & M^m \end{array} \\ \begin{bmatrix} d_{11} & \cdots & d_{1m} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{nm} \end{bmatrix} \end{array} \tag{14}$$

where d_{nm} denotes the correlation value. If the required characteristic is correlated with the design module, then the value is 1; otherwise, the value is 0.

Each module contains one or more structures to achieve the specific function; here, construct the design matrix (DM_2) for the required characteristics and the structure Str^k ($k = 1, 2, ..., p$) of M^j, as equation (15)

$$DM_2 = \begin{array}{c} \\ c(B^{1}_{\text{Pro\_Attribute}}) \\ \vdots \\ c(B^{n}_{\text{Pro\_Attribute}}) \end{array} \begin{array}{c} \begin{array}{ccc} \text{Str}^1 & \cdots & \text{Str}^p \end{array} \\ \begin{bmatrix} d_{11} & \cdots & d_{1p} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{np} \end{bmatrix} \end{array} \tag{15}$$

To analyze the low-carbon structure, construct the LCBS for each product structure, design matrix (DM_3) for Str^k, and LCBS^l ($l = 1, 2, ..., q$) as follows

$$DM_3 = \begin{array}{c} \\ c(B^{1}_{\text{Pro\_Attribute}}) \\ \vdots \\ c(B^{n}_{\text{Pro\_Attribute}}) \end{array} \begin{array}{c} \begin{array}{ccc} \text{LCBS}^1 & \cdots & \text{LCBS}^q \end{array} \\ \begin{bmatrix} d_{11} & \cdots & d_{1q} \\ \vdots & \ddots & \vdots \\ d_{n} & \cdots & d_{nq} \end{bmatrix} \end{array} \tag{16}$$

Therefore, we can obtain the direct mapping relationship of the characteristic attributes and the product LCBS, which are the object of transformation operations.

Integration of TRIZ and Extenics for low-carbon design

Both TRIZ and Extenics methods can be used to solve the contradiction problems, the purpose of proposed method is to make low-carbon design more effective and efficient by integrating the TRIZ and Extenics methods than using these two methods independently. Figure 2 shows the procedure of TRIZ and Extenics methods in design problem solving. However, both of them have weaknesses.

In TRIZ method, the first step, for more time, designers describe a problem in a qualitative way. For instance, the level of noise of the air screw compressor in our case study is unsatisfied, and carbon footprint of the machine in use phase does not meet the design specification; however, how extent the level of noise is unsatisfied, and how extent we can do to reduce the carbon footprint to meet the specification; in this aspect, TRIZ method does not form a quantitative description approach, especially in the context of a complex design system, there exist more than one design problems need to be solved, which one is emergent, which one is tough, and which one is easy, designers prefer to solve the problem in an order with its extent of importance.

The fourth step, designers get the generic solutions with the favor of TRIZ tools and knowledge base, but the generic solutions are always abstract because the

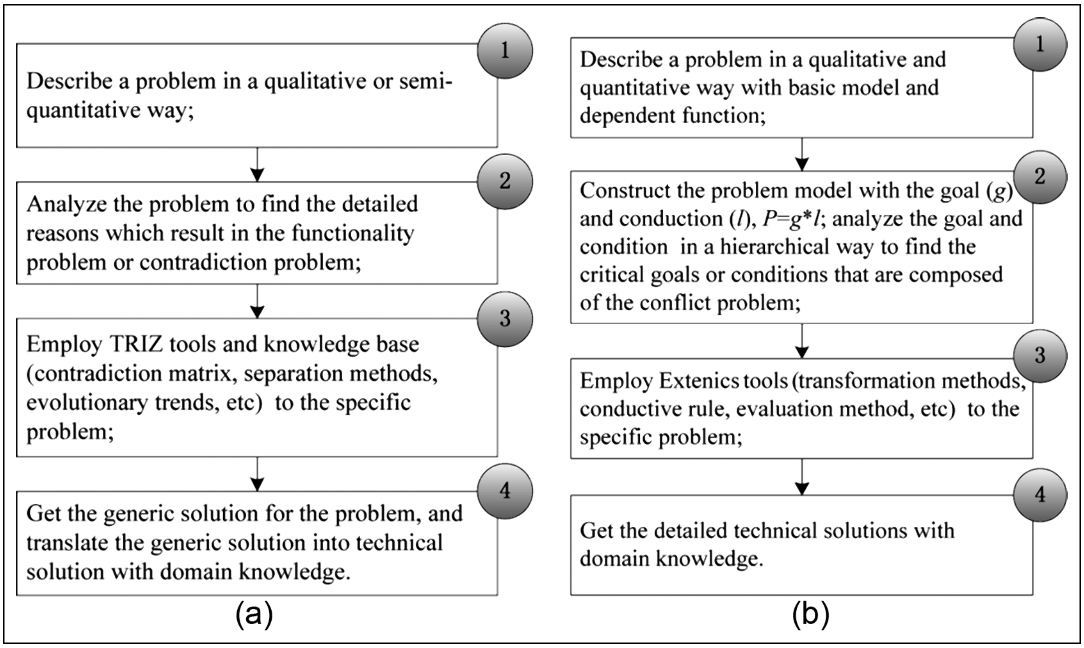

Figure 2. Procedure of design problem solving by TRIZ and Extenics methods: (a) procedure of TRIZ method and (b) procedure of Extenics method.

inventive principles are extracted from a number of patents to solve the general problem; thus, transforming the generic solutions into technical solutions depends on designers' domain knowledge.

For Extenics method, the third step, designers use the Extenics tools, the transformation methods, to modify the unsatisfied structure; however, before the detailed transformation, designers lack the inspiration from the experience or other domain knowledge. For instance, to reduce the carbon footprint of use phase in our article, we adopt the method that increase a speed-adjusting module and an air pressure–feedback module; before conducting the increasing transformation, we have already got the inspiration of "Periodic action" of inventive Principle 19 in TRIZ knowledge base.

The fourth step, Extenics method depends on the designers' domain knowledge as well in getting the detailed technical solution.

Thought of integrating the TRIZ and Extenics methods

Since these two methods have the weaknesses in solving design problems and the definitions of technical and physical contradictions in TRIZ are consistent with the representation of antithetical and incompatible problems in Extenics method, we get the thought of incorporating two methods into low-carbon design for products. TRIZ method allows one to put forward generic solution with its analysis tools and knowledge base tools, but it cannot provide the concrete transformation operations. Extenics method discusses conflict problems in a formalized model, employs the dependent function to quantitatively identify the extent of compliance with requirement and condition, and converts generic solution into specific solution by transformation tools. In this section, we give the steps of integrating TRIZ and Extenics method to solve conflict problems, and Figure 3 describes the framework of the integration method.

Step 1: retrieve the similar case and use the prior design knowledge, which we have studied in Zhao et al.;[60] Step 2: qualitatively and quantitatively represent the conflicting model for characteristics of the similar case with Extenics tools; Step 3: abstract the generic problem with TRIZ model from conflicting characteristics; Step 4: get the generic solution by TRIZ tools and knowledge base; and Step 5: transform the generic solution into specific scheme with Extenics tools and retain the newly designed knowledge for the case base.

The detailed steps of strategies for technical contradiction and antithetical problem, physical contradiction and incompatible problem are as follows.

Strategies for technical contradiction and antithetical problem

Technical contradiction in TRIZ and antithetical problem in Extenics method involve two characteristic parameters, and when one is improved, the other is degraded. Therefore, we employ contradiction matrix and inventive principles to get general strategies and

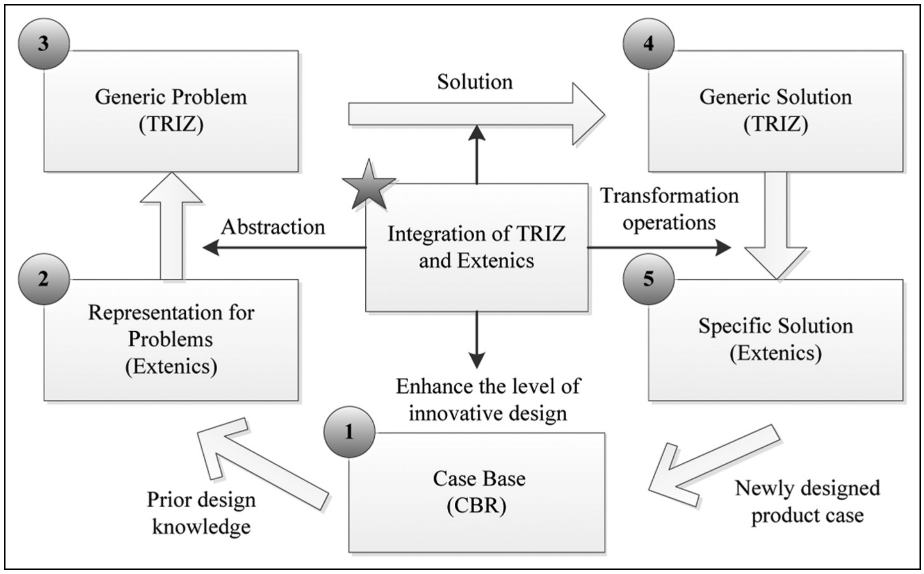

Figure 3. The framework of the integration method.

implement transformation operations based on domain expert knowledge to achieve detailed design scheme. The steps of solving the technical contradiction and antithetical problem are as follows:

Step 1: identify contradiction problem of each characteristic requirement according to dependent function.
Step 2: map the characteristic requirement onto the basic structure LCBS, and construct the conflict problem model as equation (17)

$$P_{j_1 \wedge j_2} = ((v(B^{j,j_1}_{\text{Pro\_Attribute}}) \wedge v(B^{j,j_2}_{\text{Pro\_Attribute}})) \uparrow v(PR^j))* ((\text{LCBS}^{i,k,l})_{j_1} \wedge (\text{LCBS}^{i,k,l})_{j_2}) \quad (17)$$

Equation (17) expresses that characteristics j_1 and j_2 cannot satisfy product requirement PR^j simultaneously, $j = 1, 2, ..., m_2$; $j_1, j_2 = 1, 2, ..., n$; thus, map the characteristics onto $(\text{LCBS}^{i,k,l})_{j1}$ of characteristic j_1 and $(\text{LCBS}^{i,k,l})_{j2}$ of characteristic j_2; $i = 1, 2, ..., m$ (number of modules of one characteristic); $k = 1, 2, ..., p$ (number of structures in module i); $l = 1, 2, ..., q$ (number of LCBS).

Step 3: match characteristics j_1 and j_2 to two engineering parameters Y_i ($i = 1, 2, ..., 39$), recorded as Y_{j1} and Y_{j2} according to Table 1 and search the contradiction matrix to get one or more inventive principles.
Step 4: implement transformation operations according to domain expert knowledge to transform the generic strategies to detailed schemes.
Step 5: get the feasible design schemes.

Strategies for physical contradiction and incompatible problem

Physical contradiction in TRIZ and incompatible problem in Extenics methods involve single parameter, namely, the current condition cannot satisfy the requirement. Therefore, we adopt separation method and inventive principles to get generic strategies and employ transformation operations to achieve detailed design schemes. The steps of solving physical contradiction and incompatible problem are as follows:

Step 1: identify contradiction problem of each characteristic requirement according to dependent function.
Step 2: map the characteristic requirement onto the basic structure LCBS and construct the conflict problem model as equation (18)

$$P_{j_1} = (v(B^{j,j_1}_{\text{Pro\_Attribute}}) \uparrow v(PR^j)) * (\text{LCBS}^{i,k,l})_{j_1} \quad (18)$$

Equation (18) expresses that characteristic j_1 cannot satisfy requirement PR_j under current condition, $j = 1, 2, ..., m_2$; $j_1 = 1, 2, ..., n$; thus, map the characteristic j_1 onto the $(\text{LCBS}^{i,k,l})_{j1}$, $i = 1, 2, ..., m$ (number of modules of characteristic j_1); $k = 1, 2, ..., p$ (number of structures in module i); $l = 1, 2, ..., q$ (number of LCBS).

Step 3: match one of the four separations S_i ($i = 1, 2, 3, 4$), choose one or more inventive principles under S_i according to Table 2, and generate generic strategies.
Step 4: implement transformation operations based on expert domain knowledge transforming general strategies into detailed schemes.

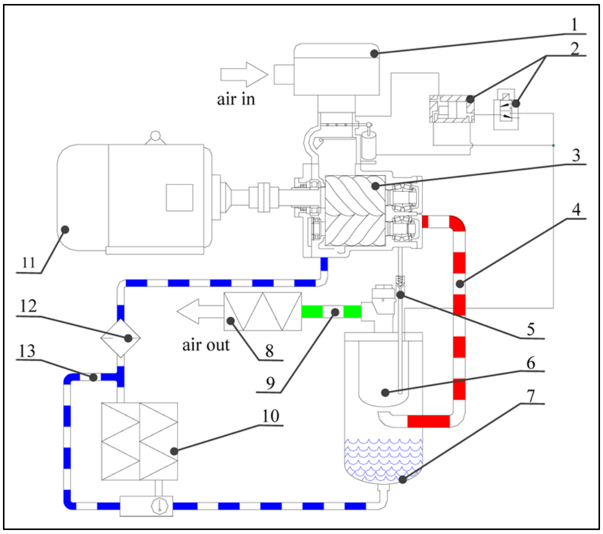

Figure 4. Functional diagram of the screw air compressor. 1: air filter; 2: control valve; 3: dual screw rotors; 4: pipeline of oil and air; 5: oil-return check valve; 6: oil/air separation core; 7: barrel of oil and air mixture; 8: the aftercooler; 9: pipeline of air; 10: oil cooler; 11: the electric motor; 12: oil filter; 13: pipeline of oil.

Step 5: get the feasible design schemes.

A case study

A screw air compressor is widely used for producing compressed air in engineering field, but it contributes to large energy consumption, big noise, and other environmental unfriendly effects in its lifetime. Therefore, low-carbon characteristics, performance characteristics should be taken into consideration in design phase. Figure 4 is the functional diagram of the screw air compressor: motor drives dual screw rotors to absorb outside air, and there are three colorful pipelines: the blue one is full of oil, the green one is full of gas, and the red pipeline denotes mixture of oil and air. In the barrel, oil is at bottom and air is above of oil. Through the oil/air separation core, we get pure air in green pipeline, and final cooling process outputs air.

In this section, we integrate the TRIZ and Extenics method to improve design scheme of the screw air compressor. In Zhao et al.,[60] we have deeply researched the retrieval and classification for screw air compressor cases; here, we take case 9 (model SA-3, similarity is 0.825) as the subject.

Identify contradiction problem of each attribute requirement

Table 3 lists the six attributes of case 9, including exhaust pressure P_{PP} (MPa), exhaust volume P_{PV} (m^3/min), noise P_{Noise} (dB), cost C_{Buy} ($\times 10^4$ Yuan), carbon footprint in use phase E_{Use} ($\times 10^5$ kgCO_{2e}), and carbon footprint of marketed product E_{Sell} ($\times 10^4$ kgCO_{2e}); desirable interval X_0 and acceptable interval X of each attribute; the optimal point x_0 in X_0; and the value of dependent function $k(A_i)$, A_i denotes the ith attribute.

In Table 3, $k(P_{PP}) = 1.5$ and $k(E_{Sell}) = 1.802$ show that these two attributes of case 9 fall into desirable interval X_0, satisfying requirement completely. $k(P_{PV}) = 0.941$ and $k(C_{Buy}) = 1$ explain that these two attributes of case 9 fall into acceptable interval X; $k(P_{Noise}) = -0.5$ and $k(E_{Use}) = -0.277$ reveal that these two attributes of case 9 fall out of X, the contradiction problems exist in attributes P_{Noise} and E_{Use}. Thus, the conflict problem is expressed as

$$\begin{cases} P = \{P_1, P_2\} * Z^{case\ 9} \\ P_1 = v(P_{Noise})_{case9} \uparrow v(PR^3) \\ P_2 = v(E_{Use})_{case9} \uparrow v(PR^5) \end{cases} \tag{19}$$

Mapping operation of conflict problems

Map the conflict problem P_1 and P_2 to the detailed LCBS based on the hierarchical analysis of the screw air compressor. Table 4 presents the design matrix DM of the module, structure, and LCBS for the screw air compressor.

In table, (0, 0), (0, 1), (1, 0), and (1, 1) denote the correlated relationships between the LCBS and the product module, structure. A value of 1 indicates that there is a perfectly correlated relationship, and a value of 0 indicates that there is no correlation.

Therefore, based on the design matrix DM, the contradiction characteristics P_{Noise} and E_{Use} can be mapped onto the basic unit. For P_{Noise}, it involves the

Table 3. Dependent function value of each attribute of case 9.

Attributes	P_{PP}	P_{PV}	P_{Noise}	C_{Buy}	E_{Use}	E_{Sell}
Case 9	1	5.6	75	4.5	1.655	1.919
X_0	(0.9, 1.1)	(3.8, 5.5)	(60, 70)	(4.5, 6.3)	(1.4, 1.6)	(1.8, 2.4)
X	(0.9, 1.3)	(3.8, 7.2)	(50, 70)	(2.7, 6.3)	(1.2, 1.6)	(1.2, 2.4)
x_0	1.1	5.5	60	4.5	1.4	1.8
$k(A_i)$	1.5	0.941	–0.5	1	–0.277	1.802

Table 4. Design matrix *DM* of the module, structure, and LCBS for screw air compressor.

Module and Structure		(P_{Noise}, E_{Use})						
System control module	Control panel	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
	Routing architecture	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
Power supply module	Motor	(0, 1)	(0, 0)	(1, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
	Power input structure	(1, 1)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(1, 1)
Air compression module	Air intake structure	(1, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
	Compression structure	(1, 1)	(0, 0)	(1, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
Oil and air separation module	Oil and air separation	(0, 0)	(1, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
	Air pressure detection	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
Compressed air cooling module	Air cooling structure	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(1, 1)	(1, 1)
	Oil loop structure	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
	Air exhaust structure	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
Vibration noise control module	Air intake structure	(0, 0)	(0, 0)	(0, 0)	(1, 0)	(0, 0)	(0, 0)	(0, 0)
	Noise insulation cover structure	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(1, 0)	(0, 0)	(0, 0)
	Damping spring	(0, 0)	(0, 0)	(1, 1)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
LCBS of screw compressor		$LCBS^1$	$LCBS^2$	$LCBS^3$	$LCBS^4$	$LCBS^5$	$LCBS^6$	$LCBS^7$

LCBS: low-carbon basic structure.
$LCBS^1$: double screw structure; $LCBS^2$: pith part of oil and air separation structure; $LCBS^3$: damping spring structure; $LCBS^4$: muffler structure; $LCBS^5$: noise insulation cover structure; $LCBS^6$: cooling fan structure; $LCBS^7$: control system structure.

$LCBS^i$ (i = 1, 2, ..., 7), and $LCBS^2$ has little effect on the noise, $LCBS^1$ and $LCBS^6$ will produce mechanical noise, $LCBS^3$ and $LCBS^7$ produce unstable noise, and $LCBS^4$ and $LCBS^5$ are the main contributors of the noise from the air intake module. For E_{Use}, it involves the $LCBS^i$ (i = 1, 3, 6, 7), and $LCBS^1$ and $LCBS^6$ mainly produce carbon footprint. Thus, detailed conflict problem can be expressed as

$$\begin{cases} P_1 = ((v(P_{Noise})_{case9} \wedge v(P_{SS})_{case9}) \uparrow v(PR^3))* \\ \quad (LCBS^4, LCBS^5) \\ P_2 = (v(E_{\text{Use}})_{case9} \uparrow v(PR^5)) * (LCBS^1, LCBS^6) \end{cases} \tag{20}$$

In equation (20), P_{SS} denotes the air admission rate of the screw compressor; it is an opposite factor to P_{Noise}. As one of them is changed, the other factor will be affected, so we need to consider the two factors together in design. Therefore, P_1 is a technical contradiction and antithetical problem and P_2 is a physical contradiction and incompatible problem.

Coordination strategies for P_1

Noise from the air intake is the main contributor, and we chose to add a muffler to reduce the noise in the air intake module. However, adding the muffler results in reducing the air admission rate, thus coordinating these two factors is the key to solving P_1.

P_{Noise} and P_{SS} can be recorded as the harmful factor and speed, respectively, so we match these two factors to the 39 engineering parameters: $P_{Noise} \equiv Y_{31}$ and $P_{SS} \equiv Y_9$. Based on the contradiction matrix, we got $M_{Y31\text{-}Y9} = \{35, 28, 3, 23\}$. After analyzing these four inventive principles, we found that $M_{Y31\text{-}Y9,3}$, namely, the Principle 3 is the most appropriate for the actual problem, and chose the suggestion C in Table 1.

The screw compressor has a low-medium frequency characteristic, so a reactive muffler was chosen, which the pipeline interface can be changed to alter the acoustic reactance and reduce the noise. The additional muffler was a single-cavity model with an expansion chamber, connected to the air intake module with an external pipe. Based on $M_{Y31\text{-}Y9,3}$ and domain expert knowledge that adopting more than one clamber cavities and modifying the interpolative pipe to the appropriate position can effectively improve the noise reducing for muffler, we employ the detailed transformation operations on the original muffler design scheme M_A

$$M_A = \begin{bmatrix} O_A & c_1 & \text{stainless steel} \\ & c_2 & \text{circle} \\ & c_3 & 60\text{ mm} \\ & c_4 & 60\text{ mm} \\ & c_5 & 180\text{ mm} \\ & c_6 & 140\text{ mm} \\ & c_7 & 1 \\ & (c_{81}, c_{82}) & 0 \\ & (l_1, l_{21}, l_{22}, l_3) & 0 \end{bmatrix}$$

Object O_A denotes design scheme A of muffler with a single-cavity structure (in Figure 5); characteristic c_i (i = 1, 2, ..., 9) denotes the attributes of muffler as follows: c_1: material, c_2: shape of cross section, c_3: inlet pipe diameter, c_4: outlet pipe diameter, c_5: expansion chamber diameter, c_6: expansion chamber length, c_7: expansion chamber cavity number, c_8: (c_{81}, c_{82})

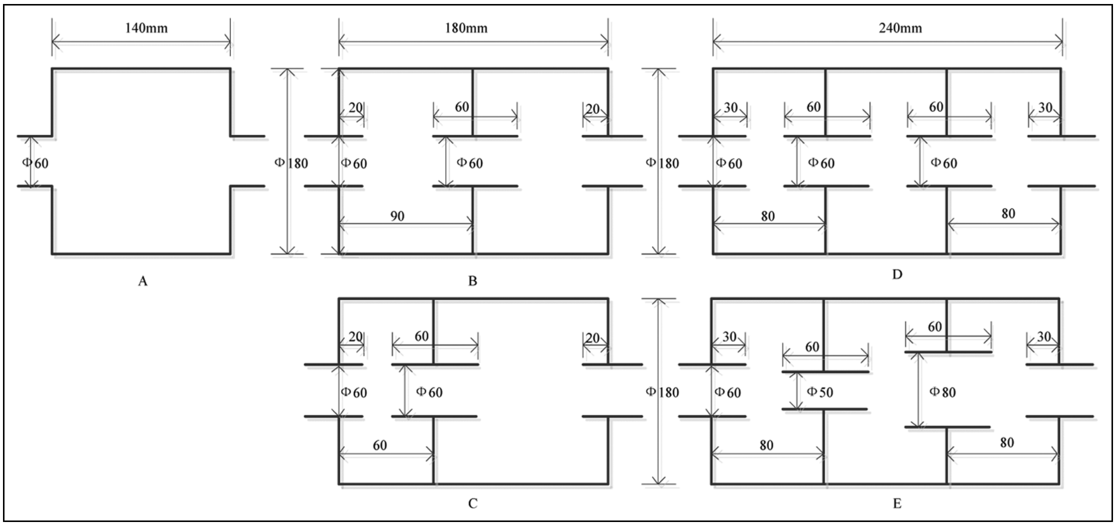

Figure 5. Transformation operation for structure design schemes of muffler.

interpolative pipe diameter, and c_9: (l_1, l_{21}, l_{22}, l_3) interpolative pipe length.

Transformations for M_A consist of structure type O_A, characteristics c_i (i = 1, 2, ..., 9) and the parameters v_i.

1. Transformation for structure type O_A: $T_{Sub}O_A = \{O_B$ = symmetrical interpolative pipe muffler with double cavities; O_C = asymmetrical interpolative pipe muffler with double cavities; O_D = equal diameter interpolative pipe muffler with three cavities; O_E = unequal diameter interpolative pipe muffler with three cavities$\}$.
2. Transformation for characteristic c_i and its parameter v_i

$$\begin{cases} T_e(c_1, v_1) = (c_1, v_1) \\ T_e(c_2, v_2) = (c_2, v_2) \\ T_e(c_3, v_3) = (c_3, v_3) \\ T_e(c_4, v_4) = (c_4, v_4) \\ T_e(c_5, v_5) = (c_5, v_5) \\ T_{\text{Dec}}T_{\text{Exp/Con}}v(c_6) = T_{\text{Dec}}(T_{\text{Exp/Con}}v(c_6)) \\ \quad = T_{\text{Dec}}(v(c_6)' = 140 \pm h \cdot 10, h \in N) \\ \qquad = \{v(c_{61}), v(c_{62}), v(c_{63})\} \\ T_{\text{Inc}}v(c_7) = v(c_7)' = \{v(c_{71}) = 1, v(c_{72}) = 2, v(c_{73}) = 3\} \\ T_{\text{Inc}}c_8 = \text{Interpolative pipe diameter} \\ T_{\text{Exp/Con}}v(c_8) = v(c_8)' = (60 \pm j \cdot 5, j \in N) \\ T_{Inc}c_9 = \text{Interpolative pipe length} \\ T_{\text{Exp}}v(c_9) = v(c_9)' = (10 + t \cdot 5, t \in N) = \{l_1, l_{21}, l_{22}, l_3\} \end{cases}$$

T_e denotes no transformation operations, and the procedure of transformation operations is as follows:

Step 1: specify the increasing transformation (T_{Inc}) for muffler cavity structure: $T_{\text{Inc}}v(c_{71}) = v(c_{7i})$, $i = \{2, 3\}$.
Step 2: specify the expansion and contraction transformation ($T_{\text{Exp}}/T_{\text{Con}}$) for $v(c_6)$ and employ the decomposition transformation (T_{Dec}) response to step1. In $T_{\text{Exp}}/T_{\text{Con}}$, $v(c_6)' = 140 \pm 10h$, $h \in N$; namely, the transformation pace is $10h$.
Step 3: increase characteristic interpolative pipe diameter c_8 and specify the expansion and contraction transformation ($T_{\text{Exp}}/T_{\text{Con}}$) for $v(c_8)$, $v(c_8)' = 60 \pm 5j, j \in \text{N}$.
Step 4: increase characteristic interpolative pipe length c_9 and specify the expansion transformation (T_{Exp}) for $v(c_9)$, $v(c_9)' = (10 + 5j,\ j \in N) = \{l_1,\ l_{21},\ l_{22},\ l_3\}$.
Step 5: evaluate the effect of noise reduction $\triangle L$ by in Editorial Board of Mechanical Design Manual[61]

$$\Delta L = 10lg\left[1 + \left(\frac{m_e}{2}\right)^2 sin^2 kl\right] \quad (21)$$

m_e denotes the expansion ratio of the inlet and outlet area, $k = 2\pi/\lambda$, and λ denotes the wavelength.

Step 6: for the muffler with two cavities: if $\triangle L_2[10,\ 14]$ dB, then save the result and return in Step 2. If NUM$\{\triangle L_2[10,\ 14]\text{dB}\} = 3$, return to Step 1 and record the number of the unsatisfied scheme with $\triangle L \not\subset [10, 14]$ dB.
Step 7: for the muffler with three cavities: if $\triangle L_2[10,\ 14]$ dB, then save the result and return to Step 2. If NUM$\{\triangle L_2[10,\ 14]\text{dB}\} = 3$, record the number of the unsatisfied scheme with $\triangle L \not\subset [10, 14]$ dB.
Step 8: end.

Table 5. Suggestions for Principle 19.

Principle 19	Suggestions
Periodic action	A: instead of continuous action, use periodic or pulsating actions B: if an action is already periodic, change the periodic magnitude or frequency C: use pauses between actions to perform a different action

Following the above steps, we select four kinds of muffler structures that have better noise-reducing performance than other schemes. The four kinds of structures are labeled B, C, D, and E in Figure 5, with A being the original muffler structure. The values of $\triangle L$ for the four structures are 10.8, 11.2, 13.1, and 13.3 dB, respectively. Here, we take the muffler with three cavities (M_E) as an example to compare to the original structure M_A

$$M_E = \begin{bmatrix} O_E & c_1 & \text{stainless steel} \\ & c_2 & \text{circle} \\ & c_3 & 60\ \text{mm} \\ & c_4 & 60\ \text{mm} \\ & c_5 & 180\ \text{mm} \\ & (c_{61}, c_{62}, c_{63}) & (80, 80, 80)\ \text{mm} \\ & c_7 & 3 \\ & (c_{81}, c_{82}) & (50, 80)\ \text{mm} \\ & c_9(l_1, l_{21}, l_{22}, l_3) & (30, 60, 60, 30)\ \text{mm} \end{bmatrix}$$

Coordination strategies for P_2

Conflict P_2 is an incompatible problem that the carbon footprint in use phase (E_{Use}) cannot satisfy requirements from customers, governmental policy, and friendly environment demand. Map E_{Use} onto the detailed structure of screw air compressor $LCSB^1$, $LCSB^6$, and reveal that E_{Use} mainly comes from the dual screw rotors, which compress air driven by a motor. Thus, we have transformed the incompatible problem E_{Use} to the detailed structure dual screw rotors ($LCSB^1$). On one hand, we hope the rotational speed of dual screw rotors is high to produce the required air pressure; on the other hand, we expect that the rotational speed of dual screw rotors is low to reduce energy consumption. Thus, rotational speed of dual screw rotors or the motor rational speed is the potential engineering parameter in physical contradiction analysis.

On this condition, we employ separation principles to separate the opposite requirements. Find the related inventive Principle 19 in *Separate in time* principle, and Principle 19 is called "Periodic Action," which contains the suggestions in Table 5.

Integrating domain expert knowledge, we take the suggestion A, use periodic and pulsating actions to replace the continuous action. Namely, adjust the motor rational speed to drive the dual screw rotors based on the feedback of the air pressure in gasholder. The problem solving strategy is shown in Figure 6.

The original scheme is that the three-phase asynchronous motor drives the dual screw rotors to compress the air and store high-pressure air in the gasholder, and it wastes energy largely as the motor works in full power state all the long time. The improved scheme is shown in Figure 6, add the speed-adjusting module and the air pressure-feedback module. The air pressure-feedback module feeds back the state of pressure fluctuation in gasholder and sends the signal to the speed-adjusting module; when the air pressure is higher than the set required air pressure range, reduce the rotational speed of the motor; otherwise, increase it. The new method adjusts the motor speed according to the feedback signal, guarantees the required air pressure, and reduces the power consumption, and thus conflict problem is solved.

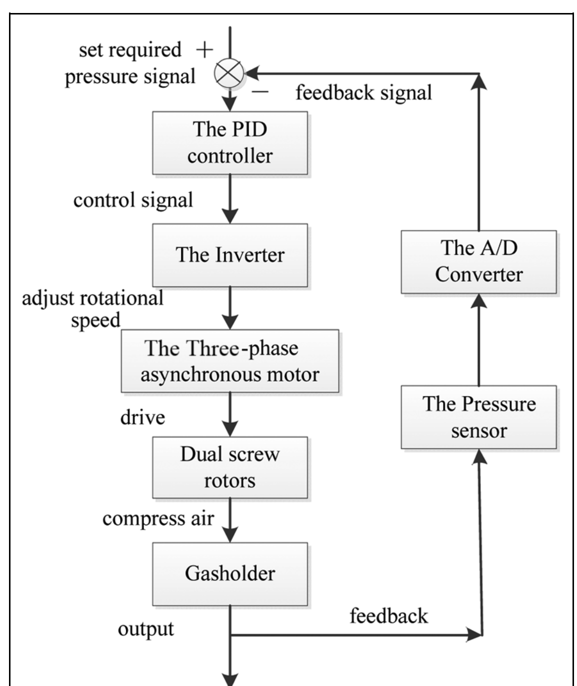

Figure 6. Problem solving strategy for P_2.

Table 6. Comparison of methods for products design.

Methods	Pros	Cons	Le-Inn	De-Eff
Brainstorm	The associative reflection is beneficial to stimulate innovative thinking of each participant in the group, and to put forward novel schemes.	High-quality requirements for participants from different departments; the high cost of time and finance.	●●	●
Checklist	Clearly list the items used for assessing a new product or a design scheme.	It is a subjective method, and it can rarely provide a concrete solution.	●	●●
QFD	Customers' requirements oriented, construct mappings between demands and product quality characteristics (QCs), between QCs and engineering characteristics (ECs), identify the most influential ECs in the function realization.	It requires extensive knowledge for designers; it lacks the instructions for the conflicts coordination with respect to the correlation matrix of QCs.	●●	●●
CBR	Store the prior knowledge in product cases without constructing complex rules; retrieve similar cases and rapidly reuse the knowledge for the new products design.	It is often used for routine design, and it is incompetent to offer ideation for innovative design when considering multiple coupled factors.	●	●●●
TRIZ method	Adopt the TRIZ tools and knowledge base to generate generic design schemes to solve contradiction problems; the design schemes across different knowledge domains and thus with high innovation level.	It describes contradiction problems in a qualitative and semi-quantitative way, which cannot identify the urgent conflicting factors in order; it lacks concrete transformation operations to convert the generic design scheme to the technical solution; and it depends on designers' knowledge and experience.	●●●	●●
Extenics method	Represent conflict problems in a qualitative and quantitative way; it can transform the generic design scheme to a detailed technical solution with concrete transformation operations.	It lacks the knowledge base and thus cannot provide inspiration instructions for designers; it depends on designers' knowledge and experience.	●●	●●
Integration method	Represent conflict problems in a qualitative and quantitative way by the basic-element and the dependent function; generate the generic design scheme by TRIZ tools and knowledge base; transform the generic design scheme to the technical solution by concrete transformation operations.	It depends on designers' knowledge and experience; it leads to the combination explosion problem in searching the better design scheme.	●●●	●●●

Le-Inn: level of innovation; De-Eff: design efficiency; QFD: quality function deployment; CBR: case-based reasoning.
●: low; ●●: medium: ●●●: high.

Discussion

Comparison of methods for products design

In addition to the TRIZ and Extenics methods, there are some common used methods for products design, the Brainstorm, Checklist, QFD, and CBR. Here, we list the pros and cons of these methods in Table 6 and make a comparison of these methods and our proposed integration method and take the level of innovation (Le-Inn) and design efficiency (De-Eff) as the comparison indices.

In Table 6, the former four methods are often used for conventional products design, although Brainstorm method has medium innovative level, the cost of time and finance is high. The Checklist method has medium design efficiency, but it can rarely put forward concrete solution. QFD is a customers' requirements oriented method and has medium performance in innovative level and design efficiency, and the competence in coordination for the conflict problems is weak. CBR method can rapidly reuse the prior design knowledge, but its innovative level is low. TRIZ and Extenics methods are mainly used for solving the contradiction problems in the innovative design, both of them have pros and cons, thus the integration method takes advantage of these two methods to accelerate the preliminary low-carbon design for products. The integration method has a high level of innovation and high design efficiency, and there is a premise that our research in this article is the successive work of the Zhao et al.,[60] which we have researched the retrieval and classification method to get the similar cases; thus, we can rapidly reuse the prior knowledge from the similar cases and deal with the contradiction problems by means of integration method. There are still disadvantages in our proposed method, it also depends on designers' domain knowledge and experience, and it contributes to the combination explosion problems; the reasons for the latter limitation are discussed in sections "Non-uniqueness of generic strategies by TRIZ" and "Diversity of transformation operation in Extenics," and our further research is to overcome the limitation of the combination explosion problem.

Relationship between contradiction problem in TRIZ and conflict problem in Extenics

In TRIZ, contradiction problem consists of technical contradiction and physical contradiction; in Extenics, it divides the conflict problem into antithetical problem and incompatible problem. In the research, we put technical contradiction and antithetical problem, physical contradiction and incompatible problem together, respectively, but it does not mean that technical contradiction equals antithetical problem and physical contradiction equals incompatible problem. Technical contradiction describes the conflicting situation during the design process. For instance, the characteristic performance P_{Noise} is not satisfied, and by means of the mapping operation, when P_{Nosie} is improved, another characteristic P_{SS} is degraded. Antithetical problem describes the extent of satisfaction between requirement and the current condition. As the same example, P_{Noise} is not satisfied, neither P_{SS}, and they cannot get improved simultaneously. Thus, in Extenics, antithetical problem is also regarded as coupled problem of two parameters. Physical contradiction involves one parameter but with two opposite requirements, which also describes the conflicting situation during the design process. For instance, the carbon footprint in use phase E_{Use} problem, and it maps onto the dual screw rotors. We expect the rotational speed of dual screw rotors is high to increase the work efficiency, while we also hope the rotational speed is low to decrease the energy consumption. Incompatible problem is an independent problem, as the same example, the rotational speed of dual screw rotors is not satisfied under current condition. Therefore, we combine the technical contradiction and antithetical problem, physical contradiction and incompatible problem, and integrate the analysis tools and knowledge base in TRIZ and the formalized representation model and transformation operations in Extenics to resolve the contradiction or conflict problem in product low-carbon design.

Non-uniqueness of generic strategies by TRIZ

In research, we adopt the inventive Principle 3 *Local quality* and Principle 19 *Periodic action* to provide general strategies for the technical contradiction and physical contradiction, respectively. However, it is not the unique strategy to solve the contradiction problem. First, matching one characteristic to 39 engineering parameters is not unique. For instance, we match the P_{Noise} to the engineering parameter 31 *Object-generated harmful factors*, and we also can match it to the engineering parameter 22 *Loss of energy*, thus we can get different general strategies. Second, classification of inventive principles to each separation method for physical contradiction is not unique. Although researchers agree with the definition of four types of separation method, they group inventive principles to the responding separation method in difference. Third, as there are one or more inventive principles in one intersection of the contradiction matrix, or under one separation method, designers may choose different inventive principles to generate generic strategy based on their domain knowledge.

Diversity of transformation operation in Extenics

When the generic strategy is chosen, detailed transformation operations start. In Extenics, it consists of *Substitution, Increasing, Expansion/Contraction, Decomposition, Duplication*, and the combination transformations. Choosing different transformation operations and implementing on different LCBSs will generate different design schemes. In antithetical problem solving of this work, we take muffler structure LCBS[4] as the transformation object. First, implement the *substitution transformation* for muffler structure with O_B, O_C, O_D, and O_E to replace the O_A; and then take *Increasing transformation* for expansion chamber cavity number, *Expansion/contraction transformation* for interpolative pipe diameter, and *Expansion transformation* for interpolative pipe length. Finally, we choose one better design scheme of each transformation for the muffler structure the M_{B}, M_{C}, M_{D}, and M_{E}. Therefore, when the number of transformation objects is large, and implement with different operations, on this condition, research of the optimal scheme selection is required.

Conclusion and future research

The CBR method can solve the routine design problem based on its prior experience; however, it is incompetent to the inventive problems. Therefore, we integrate TRIZ and Extenics method to coordinate the contradiction and conflict problems in low-carbon design for products. Technical contradiction in TRIZ and antithetical problem in Extenics both involve two parameters that cannot be satisfied simultaneously; physical contradiction in TRIZ and incompatible problem in Extenics both involve single parameter that contributes to the contradiction or conflict problem. Thus, thought of integrating two methods and taking advantages of inventive problem solving strategies is feasible. Represent and identify the conflict problem with basic-element model and dependent function in Extenics; map the unsatisfied attribute onto the detailed structures to reveal the conflicting mechanism; employ the contradiction matrix and separation methods to generate generic strategies for technical and physical contradiction, respectively; and implement transformation operations on the specific generic strategies and achieve feasible design schemes. With the proposed method, we coordinate the contradiction problem in two opposite parameters, P_{Nosie} and P_{SS}, provided with four better design schemes; solve the conflict problem in single parameter, E_{Use}, by means of adjusting the rotational speed of dual screw rotors according to the air pressure feedback.

Although the procedure of contradiction problem solving in the integration approach still depends on designers' knowledge, the purpose of our proposed method is to make low-carbon design more effective and efficient by means of integrating the TRIZ and Extenics than using these two methods independently. It is the nature of most of design methodologies that domain knowledge and experience of designers play a critical role in design activities, and our method supplies more instructions and guidelines for designers. However, there exist limitations in our method and still needs further research. As mentioned in section "Discussion," because of the non-uniqueness of generic strategies by TRIZ and the diversity of transformation operation in Extenics, which contribute to the combination explosion problem in searching the better design schemes. Thus, construct an evaluation model and adopt the evolutionary algorithm with the model to search the optimal scheme is our future research.

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