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Research Article

Conflict Resolution for Product Performance Requirements Based on Propagation Analysis in the Extension Theory

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Traditional product data mining methods are mainly focused on the static data. Performance requirements are generally met as possible by finding some cases and changing their structures. However, when one is satisfied with the structures changed, the other effects are not taken into account by analyzing the correlations; that is, design conflicts are not identified and resolved. An approach to resolving the conflict problems is proposed based on propagation analysis in Extension Theory. Firstly, the extension distance is improved to better fit evaluating the similarity among cases, then, a case retrieval method is developed. Secondly, the transformations that can be made on selected cases are formulated by understanding the conflict natures in the different performance requirements, which leads to the extension transformation strategy development for coordinating conflicts using propagation analysis. Thirdly, the effects and levels of propagation are determined by analyzing the performance values before and after the transformations, thus the co-existing conflict coordination strategy of multiple performances is developed. The method has been implemented in a working prototype system for supporting decision-making. And it has been demonstrated the feasible and effective through resolving the conflicts of noise, exhaust, weight and intake pressure for the screw air compressor performance design.

1. Introduction

Product performance not only holds the key to meeting customers' requirements but also is a factor determining enterprises' competitive advantages. Performance Driven Design (PDD) has become an important branch of the modern design theory. Product performance must be taken into account throughout the design process, and PDD becomes increasingly complicated and systematic with the design problems for different performances interacting with, and depending upon, each other. Study on the product performance can further attain its competitive advantages amongst products, which belong to the same function, the same type, or the same grade. A product's overall performance is essentially determined by the degrees of how all the customers' expectations are met as a whole. It is of significant importance to study the correlations among the various factors that influence a product's overall performance, the resolution of overall performance optimization conflict problems caused by meeting different performance requirements. Consequently, the accurate identification and effective resolution of design conflicts become a core problem for effective decision making for PDD.

The description, representation, quantification, and transformation of product performance should be studied in the first place to implement PDD. At present, a unified terminology for product performance has not yet been available and there are many different definitions given in different fields of study and for different research subjects, for example, function requirements attribute [1], function-quality evaluation system [2], and the basic characteristics of the design process [3]. Compared with product function, product performance is more fuzzy and dynamic, which generally involves function, quality, structure, material, environment, and other factors related to the design, development, and use of a product. In this research, the study of conflict coordination for PDD is based on the function-structure representation.

PDD is an innovative design method in which the realization of good function and the attainment of high quality are at the central place in the analysis, deliberation, design, calculation, and evaluation of design ideas. In the opinion of Wie et al. [4], PDD is an important part of the modern product design theory and methodology. Under the function-quality scheme, to meet customers' requirements on product performance, PDD specifically solves the problem of quantifying these requirements. In essence, PDD can be viewed as a process whereby product's performance characteristics are mapped to its structural characteristics. Researchers have done some research to facilitate the mapping process. Xie [5] proposed the method of generalized PDD which emphasizes the feedback-effect model and where the effects the product may have in the design process and the feedbacks it provides to its environment in response to the effects are modeled as performance knowledge. The knowledge can be used to describe the interactions between the whole process and its subprocesses, the interactions between the subprocesses, the interactions between the whole product and its parts, and the interactions between parts [6, 7]. In this sense, the focus of PDD is to establish the mapping process between product performance and product structure directly or indirectly. The mapping can be further used to construct the model to describe the correlation between performance parameters and structure characteristics and thus to analyze, evaluate, and coordinate design conflicts caused by different performance requirements throughout the design process.

In PDD, design conflicts are inevitable because all the performance requirements need be taken into account as a whole and, furthermore, the changes made to meet one performance requirement may affect how other requirements are met. Therefore, conflict resolution becomes a central problem in PDD. The conflict problems have been studied in design and the studies are mainly focused on the fields of concurrent design, collaborative design, axiomatic design, and multiobjective optimization. A number of conflict resolution methods have been developed and all of them have specific application areas. Firstly, the resolution methods [8–11] based on design rules reduction and design knowledge reasoning generally use design rules as the basis to implement the representation, retrieval, and reasoning of design knowledge. The main drawback of these rule-based methods is that it is difficult to develop a consistent and concise way of acquiring and representing design rules. Secondly, a number of methods have been developed to place conflict problems at the center [12–14], namely, the methods based on concurrent design, the methods based on case reasoning, the resolution strategy for layered conflicts, and the methods based on the feasibility analysis of resolution strategies. This type of conflict resolution methods can effectively solve conflict problems. However, in these methods, design conflicts are treated as being static as opposed to being dynamic and the propagation of changes made to improve product performance is overlooked.

The theory of invention problem solving (TRIZ) is an important technique for coordinating design conflicts, which offers guidelines for innovative design. It was proposed by Ahshuller's research team on the basis of analyzing 2.5 million patents around the world [15]. They made identified successful invention methods and rules from the solutions described in the patents and proposed to use these methods and rules to help designers in the solving of new problems. At present, there are a lot of scholars studying the conflict resolution method based on the TRIZ theory [16–20]. However, the application of TRIZ requires designers to have enough knowledge about TRIZ and be experienced in dealing with various design problems. In addition, the TRIZ theory aims to eliminate conflicts completely, which, under the uncertainty of the current market, seems to be impossible as the elimination a principal conflict may result in the occurring of other conflicts. Furthermore, TRIZ is used as a set of guidelines and rules that need to be understood by designers. This makes it difficult to use computer to implement automatic conflict resolution, and, as such, the cost of conflict resolution is high and the cycle for developing new technologies and applying them to real problems is long.

The Extension Theory (ET) is another important tool for conflict coordination, which emphasizes addressing the dynamic features of conflict problems by transforming the current solution space using various transformation methods. It was proposed by professor Cai et al. [21] in 1997 to formulate a model for exploring the possibility of the transformations of things and thus identifying the formal rules and methods for innovation. Later on, this method was used by researchers for solving conflict problems and so far it has been successfully applied in a number of areas such as new product development, decision making, business, and system control. It, together with TRIZ, has been studied by researchers to improve design innovation [22]. Zhao and Nan [23] applied ET to a number of design research areas such as conceptual design innovation based on ET, ET-based configuration design, and variant design and proposed an intelligent design method to solve conflict problem in design and thus provide a theoretical basis for innovative design, namely, ET-based design. ET-based design can effectively describe conflict problems and their formalized solving process, which solves dynamic conflict problems in design using various transformation methods [24]. Nevertheless, the application of the ET logic to quantitative solving and reasoning is still in the preliminary stage, which is subject to low efficiency and long development cycle.

In summary, the conflict problems in PDD are difficult to formulate, represent, convert, and resolve. In addition, the methods developed so far for resolving conflicts have various disadvantages such as being difficult to implement in a computer tool, involving a long cycle of development, and overlooking the dynamic features of conflicts. To address these disadvantages, this research aims to develop methods and tools that can facilitate designers' decision making by automatically resolving design conflicts. The ET-based design method has been chosen as a basis for this work as it offers a formalized high-level modeling scheme as well as both qualitative and quantitative reasoning methods. More importantly, the transformation methods used in ET-based design help resolve dynamic design conflicts and attain system-level optimization. This paper describes a conflict resolution method based on the ET on the basis of understanding the nature of design conflicts, developing a formalized model for applying transformations to the design space to resolve conflicts, and utilizing the logical reasoning in the ET to identify and address change propagation caused by the transformations. The conflict resolution method is implemented in a prototype system and is successfully applied to the design of a screw air compressor (Figure 13).

2. Conflict Coordination Based on Propagation Analysis for PDD

When a design solution is changed to meet one specific performance requirement, the degrees this solution meets other performance requirements are also affected; that is, design conflicts arise. As customer-centered design becomes very popular, customers' performance requirements increasingly diversify. The diversification necessitates the study of conflict resolution for effectively supporting decision making in design and drives the development of PDD. Therefore, PDD has become an important part of the modern design research [2].

Product performance involves a set of parameters that are multidimensional, time varying, and highly coupled, and its quantification and calculation are complicated. This is more evident for the products that have many modules and thus the overall performance is very difficult to evaluate as all the modules may be subject to spatial and temporal changes. Taking the calculation of the noise of a screw air compressor as an example, every module in the compressor is actually a noise source and will influence the overall noise level. However, the overall noise cannot be simply evaluated by adding up every module's noise value because the spatial layout of the modules of, and the temporal interactions between, these modules need to be taken into account.

To address these challenges, this paper presents the development of a conflict resolution method based on the ET by studying the origin, formulation, and resolution of the conflicts between different performance requirements. The framework of this research is shown in Figure 1 and the pieces of work involved are described in detail as follows.

(1) *Formulation of the Conflict Problems in PDD.* Firstly, the requirements of product performance are taken as the main design target, and the measure for the distance between two cases is improved based on the distance definition given in the ET. This improved distance measure can be used to evaluate the similarity between the required performance and the performance attained by a specific product case. Thus, the most similar cases can be found from the base and the performance requirements each of these cases fails to meet can be identified. The conflict model is then constructed by analyzing the changes that need to be made to the attributes of the cases to meet the identified requirements. On the basis of this model, the classification of the core conflict problem can be realized, the propagation of the changes made to one performance requirement to others can be established, and the strategies for coordinating conflicts by utilizing transformation of the design space and propagation of changes can be obtained.

(2) *Coordination of Conflicts between the Core Performance (Which Represents the Performance Least Met by a Product Case throughout this Paper Unless Otherwise Stated) and the Product Structure Based on Propagation Analysis.* The structure of the most similar case is studied in detail and the substructure that affects the core performance mostly is defined to create a quantitative model for the core performance. The mapping between the quantitative descriptions of product's performances and its structure is researched. The propagation of design changes, when the transformations of the design space based on the ET theory are applied, is analyzed together with its influence on the performance attributes. Eventually, the attribute value of the core performance is calculated by taking into account various attributes collectively. On the basis of this value, the design solutions that meet the core performance requirements are selected.

(3) *Conflict Coordination for PDD Based on Change Analysis and Propagation.* A number of design schemes that meet customers' requirements are obtained by optimizing the core performance. Then, the attribute value of each scheme is calculated and the values before and after transformations are analyzed to obtain the threshold for a transformation and its resultant change propagation to take place. Next, the effect of propagation and the level of propagation are studied to calculate the degree of propagation (DOP) and obtain the classification knowledge (Table 5). Eventually, the dynamic transformation mechanism between product structure and product performance is established.

3. Formulation of the Conflict Problem for PDD

Using a case base in a design environment that requires fast response can shorten design cycle and improve design efficiency. Hence, in this paper, a design conflict resolution method based on transformation and propagation of product performance attributes is developed. Based on the improved distance measure in the ET (in the ET, this distance is termed the extension distance), the distance between the required performance and the performance a specific product case can attain is calculated. In this way, the number of the performance requirements that cannot be met is found out. Then, the changes of the attribute values of these performances in the case base are analyzed, and, thus, the number of the performances in conflicts and the core performance can be obtained. At last, the classification of conflict problems can be done and the coordination strategy of conflicts can be obtained.

3.1. Identifying the Unsatisfied Performance Requirements.

The first step of the conflict resolution method is to define the performance that is not satisfied (Figure 11). Then, the conflict performance and its total number can be identified together with the correlations between the core performance and the

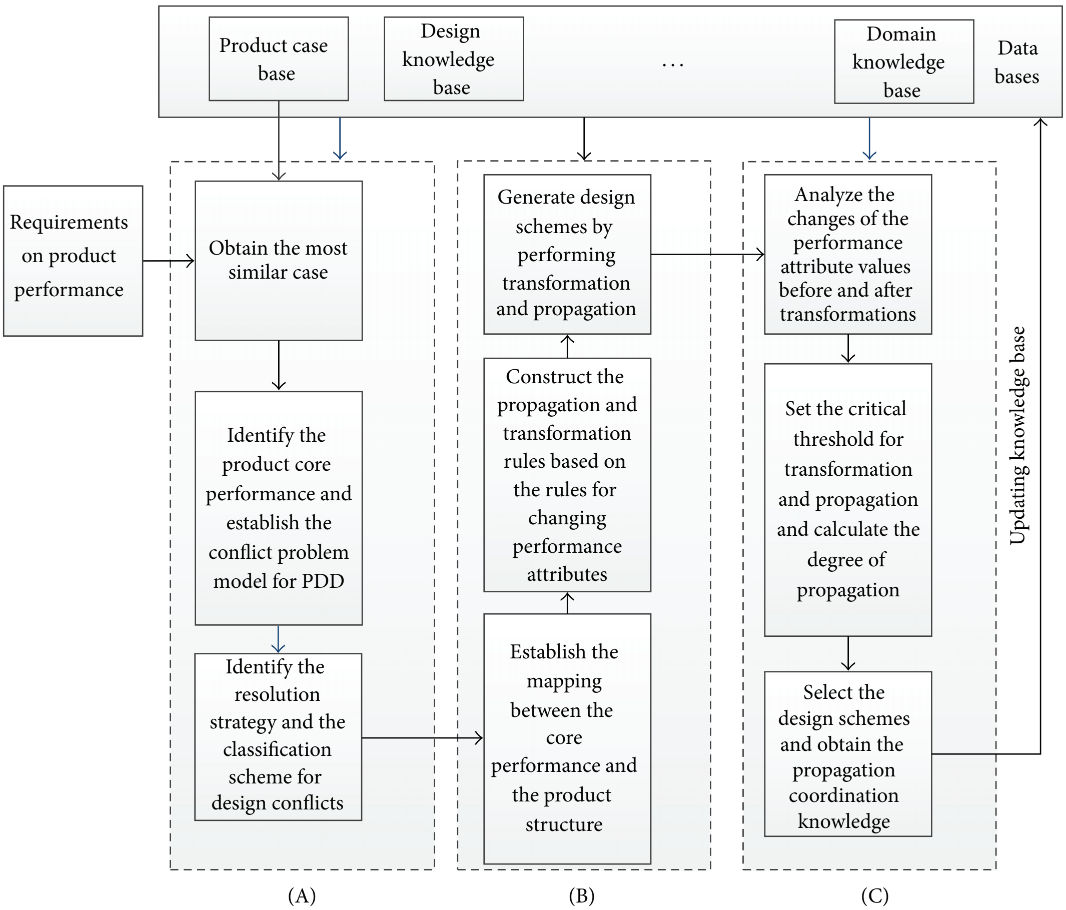


Figure 1: The framework for developing a conflict resolution method for PDD based on propagation transformation in the Extension Theory. (A) Defining the conflict problem in PDD, (B) conflict coordination between the core performance and the current product structure based on change propagation, and (C) calculation of product performance by taking into account change propagation and conflict coordination.

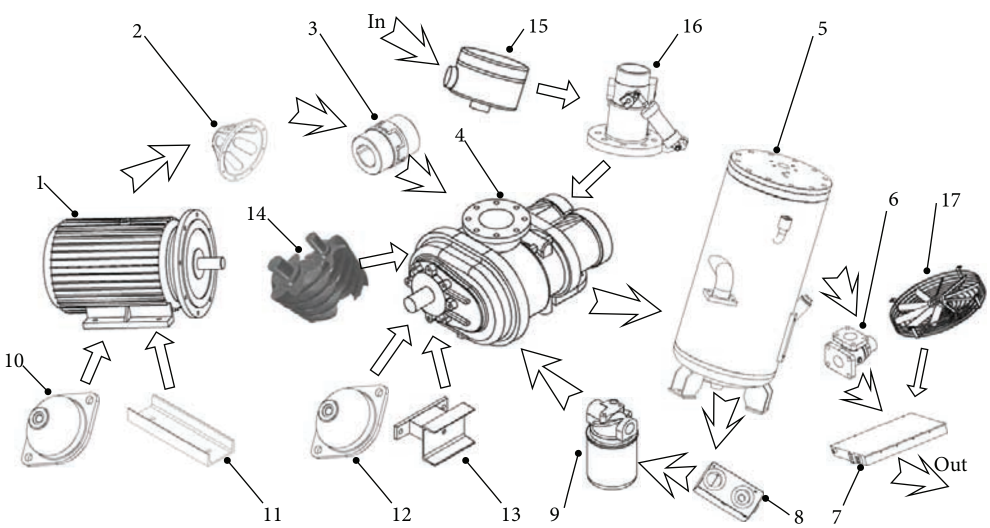


Figure 2: The main components and working schematic diagram of a screw air compressor.

Table 1: Partial data of different screw air compressors from the case base.

Model	Exhaust (m^3/min)	Exhaust pressure (Mpa)	Rated power (kw)	Noise (dB)	Weight (kg)	Fuel consumption (liter)	Stability
1-LG-1.45/10	1.45	1	11	70	500	18	Good
2-LG-15/7	15	0.7	90	90	1800	65	Best
3LG-1.2/13	1.2	1.3	11	70	500	18	Ordinary
4LG-13/7	13	0.7	75	90	1800	65	Better
5LG-2.2/7	2.2	0.7	15	70	550	18	Best
6LG-5.5/13	5.5	1.3	45	80	1100	35	Ordinary
7LG-3/7	3	0.7	18.5	74	650	20	Best
8LG-5.2/10	5.2	1	37	80	1050	35	Good
9LG-2.2/13	2.2	1.3	18.5	74	650	20	Ordinary
10LG-4.2/13	4.2	1.3	37	80	1050	35	Better
11LG-3.6/7	3.6	0.7	22	74	650	20	Better
12LG-7.2/7	7.2	0.7	45	80	1100	35	Best
13LG-1.9/10	1.9	1	15	70	550	18	Best
14LG-2.6/13	2.6	1.3	22	74	650	20	Ordinary
15LG-4.5/7	4.5	0.7	30	74	1000	35	Best
16LG-4/10	4	1	30	74	1000	35	Good
17LG-2.6/10	2.6	1	18.5	74	650	20	Good
18LG-3.4/13	3.4	1.3	30	74	1000	35	Ordinary
19LG-6/7	6	0.7	37	80	1050	35	Best
20LG-1.7/7	1.7	0.7	11	70	500	18	Better
21LG-6.3/10	6.3	1	45	80	1100	35	Good
22LG-10/7	10	0.7	55	82	1350	55	Best
23LG-1.7/13	1.7	1.3	15	70	550	18	Ordinary
24LG-8/10	8	1	55	82	1350	55	Better
25LG-3/10	3	1	22	74	650	20	Good
26LG-18/7	18	0.7	110	90	1800	65	Best

Table 2: The noise-reducing matter-element method for the screw air compressor.

Performance characteristic	Matter-element method	Configuration element set
Aerodynamic noise A_{11}	A_{111} reduces intake noise	Inlet strainer PE1 ∧ inlet muffler PE3
	A_{114} reduces fan noise	Electrical machine PE5 ∧ cooling fan PE6

others. The main measure for evaluating the degree a product meets customers' requirements is the distance between the required performance and the performance the product has attained. Since product performance generally involves multidimensional parameters with multiple units, the original data of performance need to be processed to remove the units; that is, the data is converted to values in the interval $[0, 1]$.

Actually, different extension distances describe different places from a point to an interval. Because the formula of the extension distance in [25] cannot ensure that values at the end of an interval are retrieved accurately, the right- and left-side extension distances need to be improved to address this issue, which results in the new formulas shown as follows.

The improved left-side distance applies to the situation that performance will be better when the performance value trends to be smaller in an interval $Y(y_1, y_2)$

$$d(x, Y) = \begin{cases} y_1 - x, & x \le \dfrac{y_1 + y_2}{2}, \\ x - \dfrac{y_1 + y_2}{2}, & x > \dfrac{y_1 + y_2}{2}. \end{cases} \tag{1}$$

The improved right-side distance applies to the situation that performance will be better when the performance value trends to be bigger in an interval $Y(y_1, y_2)$

$$d(x, Y) = \begin{cases} \dfrac{y_1 + y_2}{2} - x, & x < \dfrac{y_1 + y_2}{2}, \\ x - y_2, & x \ge \dfrac{y_1 + y_2}{2}. \end{cases} \tag{2}$$

Because product performance characteristics are not unique, the global similarity needs to be calculated by obtaining the values of all the local similarities collectively. The formula for the local similarity based on improved side distance is described as $V_{\mathrm{pmd}}(x, Y) = 1 - |d(x, Y)|$, and the formula for the global similarity is described as Formula (3) where $V_{\mathrm{pmd}}(x_j, Y_{ij})$ is the similarity of performance attribute between a case Y_{ij} and a design problem x_j, $R = \{x_1, x_2 \ldots, x_n\}$, and $E_i = \{Y_{i1}, Y_{i2}, \ldots, Y_{im}\}$ (the number of

TABLE 3: The muffler configuration schemes after the transformations for meeting the noise performance requirement.

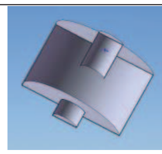
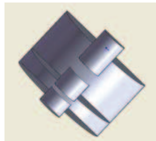
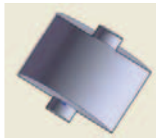
The new configuration elements of muffler	Configuration schemes	The muffler cutaway view cases after transformation	Noise reduction (dB)	Noise (dB)	Correlation degree
1	$T_4 \wedge T_1 \wedge T_1 \wedge T_1 \wedge T_1 \wedge T_2 \wedge T_2$		14.3	71.3	−0.058
2	$T_4 \wedge T_1 \wedge T_1 \wedge T_1 \wedge T_1 \wedge T_2 \wedge T_2 \wedge T_1 \wedge T_3$		18.1	68.5	0.088
3	$T_4 \wedge T_1 \wedge T_1 \wedge T_1 \wedge T_2$		12.1	74.2	−0.148

TABLE 4: Data about performance parameter of the screw air compressor before and after transformations.

Product	Noise (dB)	Intake pressure (Pa)	Rated power (kw)	Weight (kg)	Exhaust pressure (MPa)	Exhaust (m^3/min)	Fuel consumption (L)
0	80	100000	45	1100	1	6.3	35
1	71.3	99697.3	45	1124.3	1	6.28	35
2	71.3	99700.1	45	1200.8	1	6.29	35
3	68.5	99386.9	45	1130.8	1	6.24	35
4	68.5	99390.9	45	1215.1	1	6.22	35
5	74.2	99690.5	45	1122.3	1	6.27	35
6	74.2	99693.6	45	1183.3	1	6.28	35

variables in a design problem is n and the number of variables in a case is m, $m > n$). The weight of performance attribute w_j is defined through Analytic Hierarchy Process (AHP) and $\max V_{\text{amd}}(R, E_i)$ is outputted according to

$$V_{\text{amd}}(R, E_i) = \sum_{j=1}^{n} w_j V_{\text{pmd}}(x_j, Y_{ij}). \tag{3}$$

Assume $\exists V_{\text{pmd}}(x_{\varnothing}, Y_t) = 1, i < t < j$; namely, the similarity between a product case Y_t and an unsatisfied design performance characteristic $x_{\varnothing}$ is 1. According to the value of $\max V_{\text{amd}}(R, E_i)$, the number of cases with $V_{\text{pmd}}(x_j, Y_{ij}) < 1$ and its corresponding performance P_j can be defined. Then, the set of performances for which customers' requirements are not met can be described as follows:

$$S_{P_{nm}} = \{P_{nm}^{j} \mid V_{\text{pmd}}(v(P_{nm}^{j}), Y_{ij}) < 1, \quad x_j = v(P_{nm}^{j}), j = 1, 2, \ldots, n\}. \tag{4}$$

3.2. Modeling the Product Performance Conflict Problem. Since PDD involves multiple types of performance, the optimization of product performance is a multiple-objective optimization problem. To establish the conflict resolution model, quantitative description of the performance requirements needs to be obtained in an accurate way. Hence, in this work, the correlations between different performances are identified by analyzing the evolution of performance attributes for all the cases in the product case base. Assume that there are n_1 product cases, each of which is marked as PC_i where $i = 1, \ldots, n_1$, and there are n_2 unsatisfied performances, each of which is marked as P_{nm}^{ij}, where $j = 1, \ldots, n_2$. Finally, the performance instance P_{nm}^{ij} that has the minimum similarity with the required performance $\min V_{\text{pmd}}(x, Y)$ is selected as the core performance. If the product cases are ranked in a descending order in terms of their performance attribute values that are marked as $v(P_{nm}^{ij})$, then a design matrix about PC_i and P_{nm}^{ij} can be constructed as follows:

$$DM = \begin{array}{c} \\ PC_1 \\ \vdots \\ PC_{n_1} \end{array} \begin{array}{c} \begin{array}{ccc} P_{nm}^{i1} & \cdots & P_{nm}^{in_2} \end{array} \\ \begin{bmatrix} v_{11} & \cdots & v_{1n_2} \\ \vdots & \ddots & \vdots \\ v_{n_1 1} & \cdots & v_{n_1 n_2} \end{bmatrix} \end{array}. \tag{5}$$

Since each column is ranked in a descending order, then we have $v_{11} > v_{21} > \cdots > v_{n_1 1}$. Hence, this design matrix can

Table 5: Degree of propagation of the screw air compressor propagation properties.

First-order propagation	Noise (dB)	Intake pressure (Pa)	Weight (kg)	
Quadratic propagation				Exhaust (m^3/min)
γ_1	0.045	1.566	0.126	6.6×10^{-5}
γ_2	0.051	1.772	0.537	3.3×10^{-5}
γ_3	0.071	3.804	0.191	11.42×10^{-5}
γ_4	0.080	4.254	0.804	13.13×10^{-5}
γ_5	0.025	1.355	0.098	9.7×10^{-5}
γ_6	0.029	1.544	0.420	6.5×10^{-5}

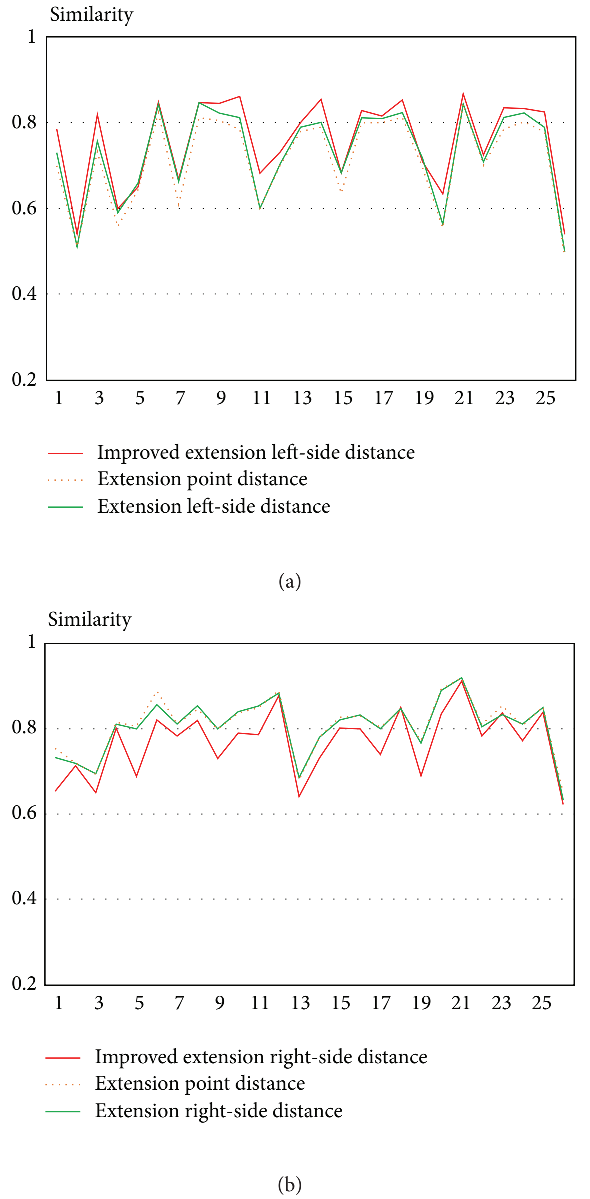


Figure 3: A comparison of retrieval performances before and after using the improved distance. (a) Comparison of the similarities between a point and an interval in terms of exhaust before and after the improved distance is used. (b) Comparison of the similarities between a point and an interval in terms of weight before and after the improved distance is used.

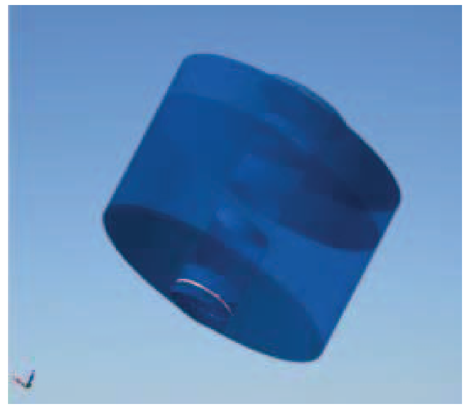


Figure 4: 3D model of the expanded muffler.

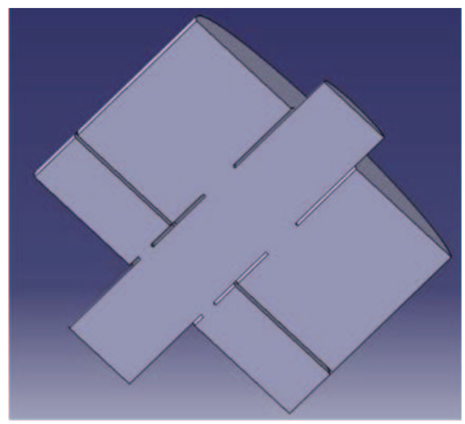


Figure 5: Cutaway view of the expanded muffler computational domain.

be calculated and converted to an upper triangular matrix as follows:

$$DM' = \begin{array}{c} \\ PC_1 \\ \vdots \\ PC_{n_1} \end{array} \begin{array}{c} \begin{array}{ccc} P_{nm}^{i1} & \cdots & P_{nm}^{in_2} \end{array} \\ \left[\begin{array}{ccc} v'_{11} & \cdots & v'_{1n_2} \\ 0 & \ddots & \vdots \\ 0 & 0 & v'_{n_1 n_2} \end{array} \right] \end{array}. \quad (6)$$

According to the above formula, we can get the conclusion that any performance attribute value can be expressed by the others' value in the matrix; for example, $P_{nm}^{ij} = P_{nm}^{1j} + P_{nm}^{2j} -$

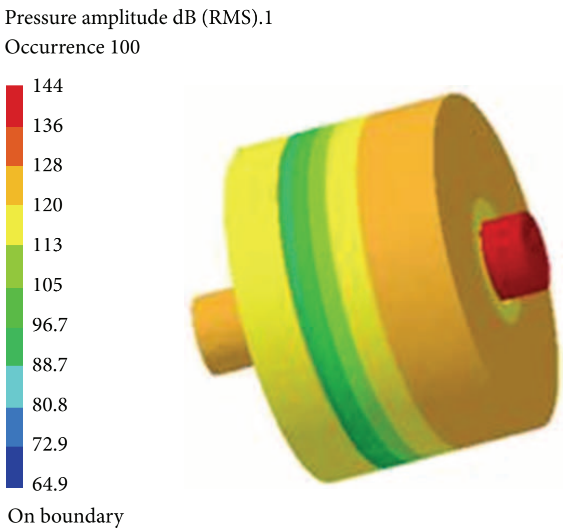


Figure 6: The picture of sound cloud of muffler.

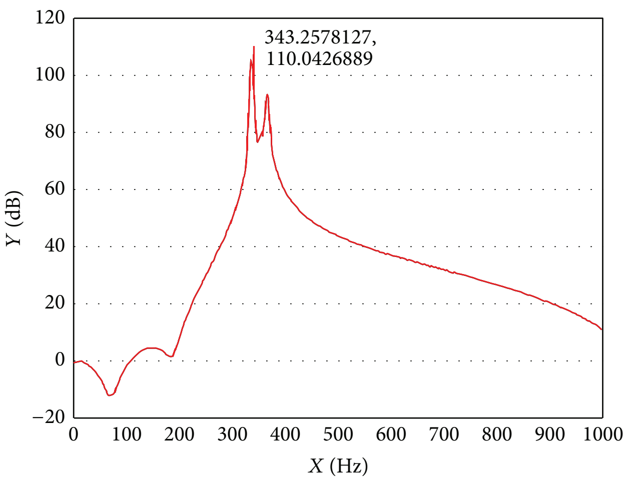


Figure 7: Transmission loss curve of pressure muffler.

Figure 8: Extension design prototype system.

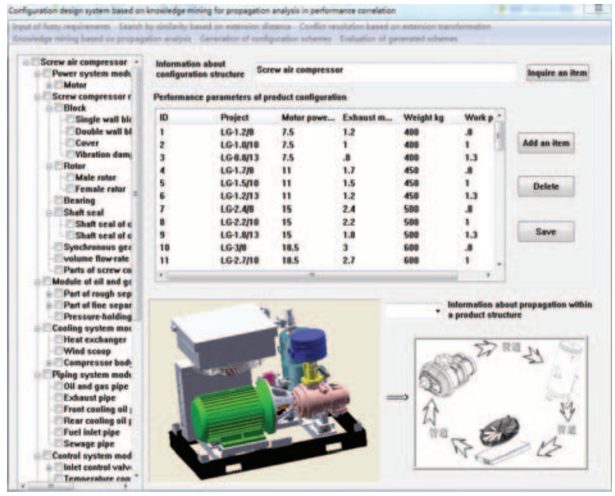


Figure 9: Graphical user interface of conflict coordination design system.

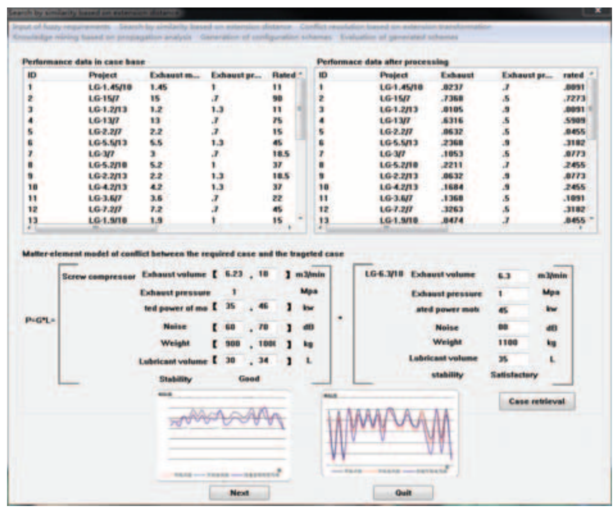


Figure 10: Performance requirements and similarities calculation.

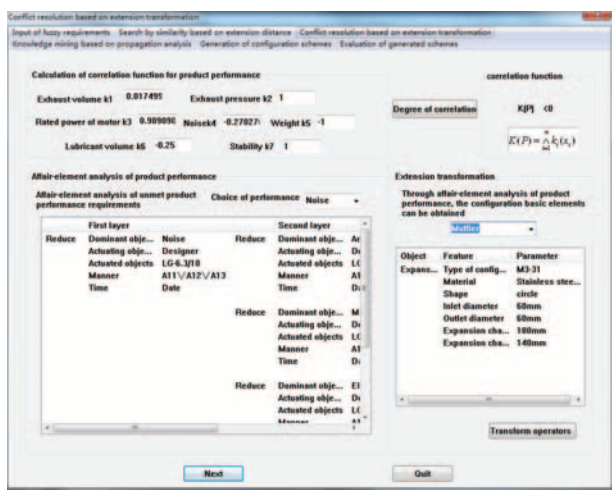


Figure 11: The conflict resolution module.

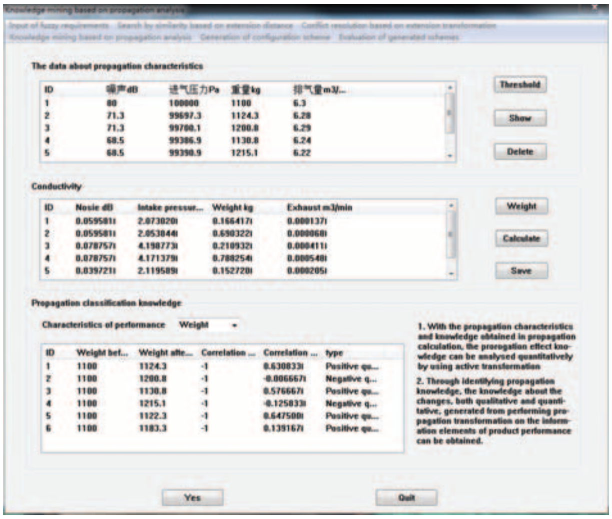


Figure 12: Propagation knowledge extraction.

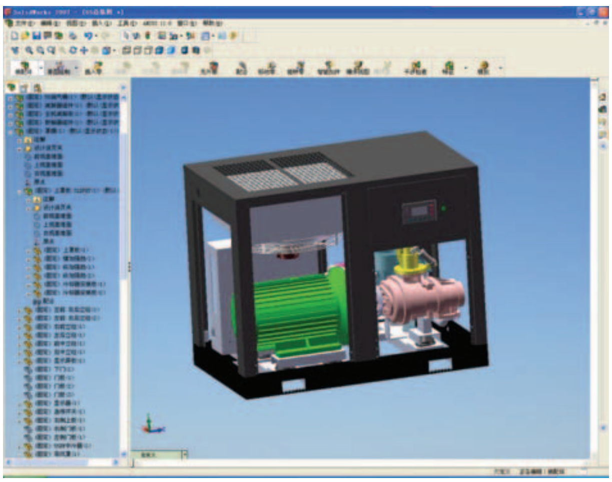


Figure 13: 3D model of the screw air compressor.

$P_{nm}^{3j} + \cdots - P_{nm}^{n_1 j}$. If $j = 1, \ldots, n_2$ is taken into the formula, the changes of other performance can be obtained when $v(P_{nm}^{ij})$ is ranked in a descending order. The signs of variables in this formula can indicate the correlations between different performance requirements; that is, a positive sign means that there are no conflicts between two performances, a negative sign means that there are conflicts, and a missing item means there is no correlation between two performances.

Therefore, a conclusion can be drawn that the overall performance requirements can eventually be met if the conflicts between the core performance and those performance requirements with negative signs in the matrix during the coordination process can be resolved. Assume that there are n_3 performances with positive signs; then the product performance conflict model can be described using the following representation, where the sign $*$ means the correlation between two variables as opposed to a logical operator:

$$Q = \left(P_{nm}^{ij} \wedge P_{nm}^{i1} \wedge \cdots \wedge P_{nm}^{in_3}\right) * CP_i. \quad (7)$$

For multiperformance optimization, the similarities between product cases are all different, the correlations between these performances are fuzzy and difficult to be determined, and an integrated quantitative mapping from performance to structure is lacking (Figure 10). When optimizing performance attributes by changing the structure parameter values, it is difficult to determine the structure parameters a specific performance attribute is related to, and, moreover, this kind of problem is subject to high complexity and low efficiency while it is difficult to implement system-level optimization and control the propagation of design changes (Figure 12). Currently, optimization for the single-performance problem mainly relies on improving the structure related to the performance according to designers' experiences.

Therefore, in this paper, the coordination process for conflict problem is divided into subprocesses. At first, conflict problem between the core performance and product structure is resolved. Next, the conflict problem in overall performance is coordinated to generate design schemes which meet customers' requirements by performing transformations and utilizing propagations.

4. Coordination of the Conflicts between the Core Performance and Product Cases Using Propagation Transformation

The essence of meeting the core performance is quantification of the correlations between performance attributes and product structure parameters and formulates them. The basic ways to solve the conflict problem in the ET-based design include (1) changing the product structure parameters, (2) changing the values of product performance attributes, and (3) changing both the structure parameters and performance attributes. Using the ET-based design method can give a formal description to the multifactor conflict problem as well as a solution process whereby conflict problems are analyzed in a dynamic way and using the combination of quantitative and qualitative methods.

4.1. Formulation of the Conflict between the Core Performance and Product Structure. Based on the conflict model of product performance, the model that describes the conflict between the core performance and product structure can be expressed as $Q_1 = P_{nm}^{ij} * CP_i$. In this expression, the performance and the product case in solving a conflict problem are given, but it could not explicitly express issues such as the correlation between the core performance and product structure and the structure parameters that most influence a specific performance attribute. Therefore, in order to describe the problem more clearly, the model should be improved by adding quantitative operations.

The core performance optimization must be implemented by representing product structure parameters quantitatively as well as by developing mathematical expressions for the calculation of performance attributes and product structures. While the number of the product structure performance is not unique and the effects on the product performance are different, the core performance structure should be used as the reference for performing propagation transformation to resolve conflict. The structure for a performance specifically refers to the minimum components that can attain a required function at an acceptable level of satisfaction.

Use P_{nm}^{ij} to represent l product structures $PS_1, PS_2, \ldots, PS_l$ and use $PSP_1, PSP_2, \ldots, PSP_l$ to represent the structure performance, so the calculation of P_{nm}^{ij} can be expressed as $v(P_{nm}^{ij}) \rightarrow v(P^i) = f[v(PSP_1), v(PSP_1), \ldots, v(PSP_l)]$, where the sign $\rightarrow$ means tend to optimization. In order to achieve the optimization of the core performance quickly, the structure performance which has the most influence on the performance should be selected as the object of transformation and propagation; that is, $CP_i = \{PS_e \mid PS_e = \max R(P_{nm}^{ij}, PSP_e),\ e = 1, \ldots l\}$.

Thus, the quantified conflict problem model can be expressed as $Q_{11} = [v(P_{nm}^{ij}) \rightarrow v(P^i)] * Z_{PS_e}$, where $[v(P_{nm}^{ij}) \rightarrow v(P^i)]$ means achieving the performance demand parameter goal, $v(P^i)$ means product case performance parameter and Z_{PS_e} means the eth-associated structure element (Table 4). The element theory in the ET uses the formalized three-tuple representation $B = (O, C, V)$ to describe a matter, an affair, or a relation where O means an object, C means the set of characteristics of object O, and V is the set of values of the characteristics. When describing a complex problem, a compound element representation is used to reduce the model dimension, being expressed as the combination of the matter-element, the affair-element, and the relation-element [26]. PS_e means the establishment of the relationship chain of the parts in a product based on the energy transfer path or power transfer path when the product is in normal work condition. Assume that a product has s parts; then it can be expressed as $PS_{e1}, PS_{e2}, \ldots, PS_{es}$; thus the conflict problem model can be further quantified to the parts layer

$$Q_{111} = \left[v\left(P_{nm}^{ij}\right) \longrightarrow v\left(P^i\right)\right] * \left\{Z_{PS_{ei}}\right\}_{i=1\sim s}. \tag{8}$$

4.2. The Propagation Process for the Conflict Coordination Method. The propagation process for conflict coordination based on transformations is to create propagation rules which are based on the parts relationship chain. In process, conflict problems are rationalized based on propagation transformation using the ubiquitous correlation and implication principle among the objects in a conflict problem. Propagation reasoning thus is the propagation transformation $({}_{\varphi}T)$ operation method caused by the active transformation (φ).

An arbitrary component element $Z_{PS_{ei}}$ is selected as the active transformation object, so that we can get $\varphi v[c(Z_{PS_{ei}})] = v'[c(Z_{PS_{ei}})]$. This will generate two kinds of propagation processes and their respective propagation rules are summarized in the following formal representations. The setting, priority, and selection of, and the weight assignment for, different transformation types are beyond the scope of this paper and can be found in the literature [25].

(1) The propagation reasoning based on component object's own features and values is as follows:

propagation rule 1: propagation transformation based on the object:

$$\begin{aligned}\left({}_{\varphi}T_{j} Z_{PS_{ei}} = Z'_{PS_{ei}}\right) &\vDash \left({}_{Z_{PS_{ei}}}T_{j}(c, v) = \left(c', v'\right)\right) \\ &\vDash k'\left(c'\left(Z'_{MP_{xi}}\right)\right);\end{aligned} \tag{9}$$

$$\text{if } k' < 0,\ \text{then } j = j + 1;\ \text{do } {}_{j}T_{j+1},\ \text{until } k' > 0;$$

propagation rule 2: propagation transformation based on the feature values:

$$\begin{aligned}&\left({}_{\varphi}T_j\, c_t\left(Z_{PS_{ei}}\right) = c'_t\left(Z_{PS_{ei}}\right)\right) \\ &\vDash \left({}_{c_t\left(Z_{PS_{ei}}\right)}T v_t = v'_t\right) \\ &\vDash {}_{v'_t}T\left(\{c_t\}, \{v_t(c_t)\}\right) = \left(\{c'_t\}, \{v'_t(c'_t)\}\right) \\ &\vDash k\left(\left\{c'\left(Z_{PS_{ei}}\right)\right\}\right);\end{aligned}$$

$$\text{if } k' < 0,\ \text{then } j = j + 1,\ t = t + 1;\ \text{do } {}_{j}T_{j+1}^{t+1},\ \text{until } k' > 0. \tag{10}$$

(2) The propagation reasoning based on component object's own features and relationship chain is as follows:

propagation rule 3:

$$\begin{aligned}\left({}_{\varphi}\{T\}\, Z_{MP_{ei}} = Z'_{MP_{ei}}\right) &\vDash \left({}_{Z_{MP_{ei}}}TZ_{MP_{ej}} = Z'_{MP_{ej}}\right)_{j \neq i \in s} \\ &\vDash K\left(Z'_{MP_{ej}}\right) = k\left[f\left(c\left(Z'_{MP_{ej}}\right)\right)\right];\end{aligned}$$

$$\text{if } k_t < 0,\ \text{then } \varphi = \varphi_{k_t<0}^{t+1};\ \text{do } {}_{\varphi_{k_t>0}^{t+1}}\left\{T^{t+1}\right\},\ \text{until } k_{t+1} > 0. \tag{11}$$

$\varphi_{k_t<0}^{t+1}$ means the $(t+1)$th-order active transformation values which are determined by the tth-order propagation transformation, $t = 0 \sim n$.

Then the performance and product structure conflict based on the propagation rules can be quantitatively expressed as

$$\begin{aligned}(\varphi,T)\,Q &= (\varphi,T)\left\{\left[v\left(P_{nm}^{ij}\right)\longrightarrow v\left(P^{i}\right)\right] * \left\{Z_{PS_{ei}}\right\}_{i=1\sim s}\right\}\\ &= (\varphi,T)\left[v\left(P_{nm}^{ij}\right)\longrightarrow v\left(P^{i}\right)\right]\\ &\quad * (\varphi,T)\left\{Z_{PS_{ei}}\right\}_{i=1\sim s}\\ &= \left[f\left\{v\left(PSP_{e}\right)\right\}\overset{(\varphi,T)}{\longrightarrow} v\left(P^{i}\right)\right]\\ &\quad * \varphi Z_{PS_{ei}} \wedge {}_{\varphi}\{T\}\left\{Z_{PS_{ej}}\right\}_{j\neq i}\\ &= \left[f\left\{v\left(PSP_{e}\right)\right\}\overset{(\varphi,T)}{\longrightarrow} v\left(P^{i}\right)\right]\\ &\quad * \left[\varphi,\ {}_{\varphi}\{T\}\right]\cdot\left[Z_{PSi},\ldots,Z_{PS_{es}}\right]^{TM}\\ &= k'\left[f\left(v\left[cPS_{ei}\right]\right),\ldots,\left(v\left[cPS_{es}\right]\right)\right]_{(\varphi,\,{}_{\varphi}\{T\})\cup v(P^{i})}.\end{aligned} \tag{12}$$

In this expression, TM means transposition; $f(\cdot)$ means the integration function; and $k(\cdot)$ means the correlation function. The correlation function is at the center place in the solving of conflict problem using the ET theory, which is constructed using the extension distance. In this sense, only when $k(\cdot) > 0$ can a conflict problem be coordinated.

The algorithm for resolving conflicts between performance attributes and structure parameters using propagation transformation is explained as follows.

Step 1. For $\{Z_{PS_{ei}}\}_{i=1\sim s}$, a group φ is given arbitrarily. Perform active transformation on the feature and then generate a group of propagation transformations ${}_{\varphi}\{T\}$ according to the propagation reasoning rules discussed above.

Step 2. For the transformation performed, evaluate the propagation effect, the degree of propagation, and the correlation formula [27]; calculate the value for each function so as to identify the direction of the transformation.

Step 3. Evaluate the feasibility of the propagation transformations performed; calculate the values of $v(PS_e)$ and $v(P_{nm}^{ij})$; find out if the condition $k'[f(v[c(PS_{ei})],\ldots,v[c(PS_{es})])]_{(\varphi,\,{}_{\varphi}\{T\})\cup v(P^{i})}$ is met; if it is met, then output the scheme as a potential solution and jump to Step 5; otherwise, jump to Step 4.

Step 4. Perform multiple-order propagation transformation; perform the assignments of $\varphi = \varphi_{k_t<0}^{t+1}$ and ${}_{\varphi_{k_t<0}^{t+1}}\{T^{t+1}\}$ based on the results obtained from the last transformation; assign $t = t++$, $t = 0 \sim n$; jump to Step 1.

Step 5. End the process; output the set of feasible propagation coordination schemes.

Through the coordination of the conflicts between performance attributes and structure parameters, a variety of product structure transformation design schemes are obtained as well as the knowledge about performing propagation transformation to meet performance requirements. However, the overall satisfaction degree of product performance also needs to be evaluated even though a single-performance attribute is met. Thus, the feasibility, advantages, and disadvantages of the design schemes generated after the propagation transformations can be further evaluated to support designers to make informed decisions.

5. The Coordination of Design Conflicts Based on Transformation of Product Structure and Propagation Analysis

In the PDD, when some of customers' performances requirements are met, the structure parameters that are correlated with these requirements will be changed to achieve improved satisfaction. However, currently, design engineers mostly change the structure of a product using their experiences firstly and then test the resultant design to see whether some performance requirements are better met. This process greatly relies on the expertise of engineers and generally leads to longer development time so that customers' new requirements cannot be met in a swift way. In addition, this method pays little attention to analyze and use the data generated after the transformations are performed, leading to the situation that the influences of these transformations on other performances are overlooked and the correlations between the data are also not utilized properly. Knowledge mining based on propagation analysis is a data mining method that is specifically used to resolve conflict problems. This method can help designers make informed decisions in the design process through analyzing the correlations between performance attributes and structure parameters before and after transformations are performed and thus providing new knowledge on the resolving of conflict problems.

5.1. The Determination of Propagation Properties Based on the Designing Schemes Generated after Transformations. Through the transformation of a product structure, an expected performance value can be achieved, while the transformation may result in changes to other performances. The inherent relationship between the performances and the change of performances in the product instance can be obtained, but it is hard to determine where these changes come from and whether these changes happen actively or are the results of the propagation process. The conflict model for all the performances can be represented as

$$\begin{aligned}Q_2 &= \left(v\left(P_{nm}^{ij\prime}\right)\wedge v\left(P_{nm}^{i1}\right)\wedge\cdots\wedge v\left(P_{nm}^{in_2}\right)\right)\\ &\quad * \left(c\left(Z'_{PC_i}\right)\cup v\left[c\left(Z'_{PC_i}\right)\right]\right).\end{aligned} \tag{13}$$

Other performance values of the product when its core performance is satisfied can be calculated after the change of product's structure. The determination of propagation performance is based on two parameters, namely, the propagation effect and the propagation sensitivity. The latter parameter ϑ means that other performance parameters have a change and the range of the change exceeds the threshold value of the propagation effect. The former refers to the d-value of the product performance parameters before and after the transformation; namely, $\Delta P_i = |P_i - P_i'|$. Then, the d-value of all products performance before and after the transformation can be calculated; only if $\Delta P_i > \vartheta > 0$, this performance is called the propagation object. On this basis, according to the propagation process, the level of propagation performance can be determined.

The degree of propagation is used to reflect the degree that changes to one product's performance parameters are propagated to others in the process of the propagation. The bigger the degree of propagation, the more obvious the propagation effect expression and it will the higher the correlation between two performances reflect. To resolve the problems that involve multiple active transformations and multiple-level propagations, the integrated degree of propagation can be constructed as follows:

$$\gamma = \frac{\left|P^i - P^{i\prime}\right|}{\sum \lambda_i \left\{\Delta v\left(c\left(PS_{ei}\right)\right)\right\}}. \tag{14}$$

5.2. The Classification Method for the Performance Propagation Knowledge. The extension set in the ET theory is an important tool of the classification of the propagation knowledge, which includes the basic element $Z_{PS_{ei}}$ and the correlation function of performance attributes values $k[f(v[c(PS_{ei})], \ldots, v[c(PS_{es})])]$. And, after finishing a group of transformations, the extension correlation function can be expressed as $k'[f(v[c(PS_{ei})], \ldots, v[c(PS_{es})])]_{(\varphi, {}_{\varphi}\{T\}) \cup v(P^i)}$. Then the extension set can be expressed as

$$\begin{aligned} \widetilde{E} = \Big\{ \left(Z_{PS_{ei}}, h, h'\right) \mid Z_{PS_{ei}} \in \left\{Z_{PC_j}\right\}, \\ h = k\left[f\left(v\left[c\left(PS_{ei}\right)\right], \ldots, v\left[c\left(PS_{es}\right)\right]\right)\right], \\ h' = k'\left[f\left(v\left[c\left(PS_{ei}\right)\right], \ldots, v\left[c\left(PS_{es}\right)\right]\right)\right]_{(\varphi, {}_{\varphi}\{T\}) \cup v(P^i)} \Big\}. \end{aligned} \tag{15}$$

The greatest characteristic of the classification based on the extension set is that it can deal with dynamic data. Existing classification methods are mostly focused on static data and fail to take the classification of the performance attributes into account after transformation. In this paper, the focus is on identifying the dynamic propagation knowledge caused by transformation. The purpose of the classification is to obtain the following transformation types:

$$\begin{gathered} \left[E_+^i \longrightarrow \dot{E}_+^i\left({}_{P_j}TP_i\right)\right] \cup \left(P_i \longrightarrow P_i'\right) \\ E_-^i \longrightarrow \dot{E}_+^i\left({}_{P_j}TP_i\right) \\ E_0^i \longrightarrow \dot{E}_+^i\left({}_{P_j}TP_i\right) \\ E_0^i = \dot{E}_0^i\left({}_{P_j}TP_i\right) \cup \left(P_i = P_i'\right). \end{gathered} \tag{16}$$

In the above expression, E_+^i, E_-^i, E_0^i, $\dot{E}_+^i({}_{P_j}TP_i)$, and $\dot{E}_0^i({}_{P_j}TP_i)$ represent the positive domain, the negative domain, the zero frontiers, the qualitative change domain, and the extension frontier of the performance parameter, respectively.

5.3. The Algorithm for Performance Conflict Coordination Based on Propagation Analysis for Product Configuration Design

Step 1. Find a product case that matches the expected requirement and obtain the performance data $v\{P^{ij}\}$ of the case; then obtain the product performance data set $\{v\{P^{ij}\}, v\{P^{ij\prime}\}\}$ after a variety of transformations $(\varphi, {}_{\varphi}\{T\})$ of the case's structure.

Step 2. Calculate $\Delta v(P^{ij})$, the differences between the performance data set before and after a transformation, and judge the propagation properties by the given threshold δ_{ij}.

Step 3. Obtain the information of propagation performance properties that changed before and after transformation; then calculate the degree of propagation $\gamma = |P^i - P^{i\prime}| / \sum \lambda_i \{\Delta v(c(PS_{ei}))\}$ of the propagation properties caused by all the active transformations, to judge the degree of changes for other performances.

Step 4. Extract the knowledge of the propagation transformation; obtain the design schemes generated after the transformation and propagation using positive qualitative change and positive quantitative change based on the extension set $\widetilde{E}$.

Step 5. Extract the rules for transformation and propagation and store them in the rule base.

6. A Case Study

Compressed air is the second largest energy after electricity, as well as being used as a gas source in industrial processes with multiple usages. Screw air compressor, as a power system utilizing the compressed air power, is used in many industrial sectors such as petroleum, chemical engineering, electric power generation, mechanical engineering, the textile industry, automotive engineering, food, medicine, biochemical, and defense. A screw air compressor is mainly composed of the motor oil-gas separate barrel, the cooling system, the air-conditioning system, the lubricating system, the safety valve, and the control system. The structure of a particular compressor studied in this research is shown in Figure 2. As shown in the figure, it consists of the following components: 1: 55 kw motor (10: absorber component; 11: motor vibration damper); 2: center rest; 3: couping component; 4: head assembly (12: absorber component, 13: host damping frame, 14: male and female rotors, 15: air filter assembly, and 16: inlet valve component); 5: oil and gas separator component; 6: minimum pressure valve; 7: intercooler; 8: thermostat valve; 9: oil filter component; 17: axial flow fan assembly.

The improved left-side distance is evaluated by calculating the similarities (shown in Figure 3(a)) between the partial cases in the case base (detailed data shown in Table 1) and a product with an expected exhaust value (between 6 m^3/min and 10 m^3/min). The same evaluation has also been done for the right-side distance in the retrieval for a compressor with a weight between 550 kg and 650 kg, with detailed comparison of case retrieval results shown in Figure 3(b). By comparing the similarities calculated using different methods (extension point distance, left-side distance and right-side distance, improved left-side distance, and improved right-side distance) for the retrieval, it is shown that the improved left-side and right-side distances achieve better retrieval precision than other methods.

(1) *The Determination of Conflict Problem in the Product's Performance.* The performance requirement of the screw air compressor can be expressed using the model as follows:

$$\begin{bmatrix} \text{screw air compressor} & \text{exhaust} & [6,10]\ \text{m}^3/\text{min} \\ & \text{exhaust pressure} & 1\ \text{Mpa} \\ & \text{rated power} & [17,23]\ \text{kw} \\ & \text{noise} & [60,70]\ \text{dB} \\ & \text{weight} & [550,650]\ \text{kg} \\ & \text{fuel consumption} & [19,24]\ \text{L} \\ & \text{stability} & [9.6,10.4] \end{bmatrix}. \quad (17)$$

Partial data about different screw air compressors from the case base is shown in Table 1, which is searched through for similar cases using the methods discussed above.

The similar matrix is constructed with the numbers obtained using the formulas for local similarity:

$$s = \begin{bmatrix} 0.6553 & 1 & 0.9182 & 0.975 & 0.9262 & 0.9184 & 0.95 \\ 0.7369 & 0.8 & 0.3636 & 0.725 & 0.1144 & 0.1224 & 0.8833 \\ 0.6421 & 0.8 & 0.9182 & 0.975 & 0.9262 & 0.9184 & 0.7166 \\ 0.8421 & 0.8 & 0.5 & 0.725 & 0.1144 & 0.1224 & 0.8833 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0.8947 & 1 & 0.6818 & 0.875 & 0.4465 & 0.3265 & 0.8833 \\ 0.7369 & 1 & 0.9818 & 0.935 & 0.9631 & 0.9592 & 0.95 \\ 0.579 & 0.8 & 0.1818 & 0.725 & 0.1144 & 0.1224 & 0.8833 \end{bmatrix}. \quad (18)$$

The weights of different performances are calculated using the AHP method:

$$w = [0.3691, 0.2417, 0.0675, 0.1334, 0.0406, 0.0267, 0.1212]. \quad (19)$$

The overall similarity between customers' performance requirements for a screw air compressor and performance attributes of the compressors in the case base is calculated according to the formula of global similarity which is represented as $\text{sim}(R, E_i) = \sum_{j=1}^{n} w_j \text{sim}(R_i, E_i)$:

$$\text{sim}(R, E_i) = [\,0.7850\ \ 0.5406\ \ 0.8183\ \ 0.5992\ \ 0.6499\ \ 0.8476\ \ 0.6676\ \ 0.8467\ \ 0.8448\ \ 0.8613\ \ 0.6820\ \ 0.7319\ \ 0.8001\ \ 0.8544\ \ 0.6828\ \ 0.8281\ \ 0.8153\ \ 0.8527\ \ 0.7087\ \ 0.6336\ \ 0.8673\ \ 0.7245\ \ 0.8346\ \ 0.8327\ \ 0.8249\ \ 0.4542\,]^T. \quad (20)$$

According to the calculation result, the product case (LG-6.3/10) will be selected for its max $V_{\text{amd}}(R, E_i)$ value.

(2) *Conflict Coordination Using Transformation and Propagation.* Noise is identified as the performance attribute to be optimized after analyzing the performance attribute values of the most similar case and the values of the required performance. The model for describing the conflict between product performance and product structure can be described as follows:

$$Q = G * L = [P(80 \longrightarrow 40)] * \begin{bmatrix} \text{Expansion type silencer} & \text{Material} & \text{Corrosion resistant plate} \\ & \text{Shape} & \text{Circle} \\ & \text{The diameter of entrance} & 60\ \text{mm} \\ & \text{Outlet diameter} & 60\ \text{mm} \\ & \text{Expansion type diameter} & 180\ \text{mm} \\ & \text{Expansion type length} & 140\ \text{mm} \end{bmatrix}. \quad (21)$$

The correlation model for calculating the values of noise and structure properties of the screw air compressor is established according to resistance muffler which belongs to low-frequency noise. The noise reduction formula of resistance muffler can be calculated using the method discussed in literature [28]. The most similar case does not meet the noise requirements and does not have an inlet muffler mounted. Since the fundamental frequency of different type of inlets is different and the most similar case's fundamental frequency is 99 MHz, there are no mufflers in the case base that can meet the requirement. Thus, the method based on transformation and change propagation is used to resolve the conflict. In this case, the conflict problem is resolved using several transformations by several main matter-element paths after comparing several aerodynamic noise characteristics and the noise value, as shown in Table 2.

The structure of muffler after transformation is got and shown as follows by using the propagation coordination algorithm:

$$\left(t_{29}^{2} \wedge t_{110}\right) l' = \begin{bmatrix} \text{Expansion type silencer} & \text{Material} & \text{Glass steel} \vee \text{galvanized steel sheet} \\ & \text{Shape} & \text{Circle} \\ & \text{Entrance diameter} & 85\,\text{mm} \\ & \text{Exit diameter} & 85\,\text{mm} \\ & \text{Expansion type diameter} & 340\,\text{mm} \\ & \text{The first expansion chamber} & 161.5 \\ & \text{The second expansion chamber} & 58.4 \end{bmatrix}. \quad (22)$$

Currently, there are no accurate calculations methods for machine noise; the overall noise cannot be obtained by simply adding all the noise sources. Assume that the noise intensities of k noise sources are $n_1, n_2, \ldots, n_k$; the overall unit noise z_n is $z_n = \log(10^{n_1} + 10^{n_1} + \cdots + 10^{n_k})$. Actually some measures to reduce noise are taken; the overall unit of actual noise f when the noise reduction is considered is the difference of the total noise and noise reduction sound intensity and can be described as $z_r : z = z_n - z_r$. The design schemes generated to meet the noise performance are shown in Table 3.

The interface between the muffler and other components is not changed during the propagation process, and, as such, other models remain unchanged.

(3) *Knowledge Mining for the Conflict Resolution Process.* Data about the performance attributes of the compressor after transformations is obtained through both theoretical calculations and simulation, which are added to the performance database after the transformations. For example, the formula of pressure loss due to friction between the inner wall of muffler and airflow is calculated as follows:

$$\Delta P_f = 10\xi_l \frac{\rho v^2}{2g} + 10\xi_f \frac{a}{d_e} \frac{\rho v^2}{2g}. \quad (23)$$

In the formula, ΔP_f is the friction resistance (Pa), ξ_f is the coefficient of friction resistance, α is the effective length of muffler(m), d_e (for a rectangular tube: $d_e = 2ab/(a+b)$) is the equivalent diameter of muffler passage (m), the air density is $\rho = 1.29\,\text{kg/m}^3$, v is the velocity of flow (m/s), and g is the acceleration of gravity.

Data about performance parameter of the screw air compressor before and after transformations are obtained through theoretical calculations.

Propagation of every performance propagation property for the screw air compressor after multiple active transformations is got according to the calculation steps discussed in the previous sections. Parameters set of multiple active transformations is got through doing multiple active transformations to the muffler discussed in Section 4

$$\begin{aligned} V_i\left(v_j, v_j'\right) &= \{V_1, V_2, \ldots, V_6\} = \left\{\left\{\left(v_1, v_1'\right), \ldots, \left(v_5, v_5'\right)\right\}; \ldots; \left\{\left(v_1, v_1'\right), \ldots, \left(v_8, v_8'\right)\right\}\right\} \\ &= \{\{(9500, 5000), (60, 85), (60, 85), (180, 340), (140, 161.5)\}; \\ &\quad \{(9500, 6000), (60, 85), (60, 85), (180, 340), (140, 161.5)\}; \\ &\quad \{(9500, 5000), (60, 85), (60, 85), (180, 340), (140, 161.5), (0, 80.75), (0, 40.35)\}; \\ &\quad \{(9500, 6000), (60, 85), (60, 85), (180, 340), (140, 161.5), (0, 80.75), (0, 40.35)\}; \\ &\quad \{(9500, 5000), (60, 85), (60, 85), (180, 340), (140, 161.5), (0, 80.75), (0, 40.35), (161.5, 58.5)\}; \\ &\quad \{(9500, 6000), (60, 85), (60, 85), (180, 340), (140, 161.5), (0, 80.75), (0, 40.35), (161.5, 58.5)\}\}. \end{aligned} \quad (24)$$

The weight of the active transformation is gained using the AHP method:

$$\begin{aligned} \text{AHP}\left(\sum_{i=1}^{h} \lambda_i\right) &= \{(0.030, 0.096, 0.074, 0.520, 0.280); (0.024, 0.109, 0.090, 0.427, 0.242, 0.059, 0.049); \\ &\quad (0.018, 0.132, 0.114, 0.353, 0.195, 0.041, 0.036, 0.111)\}. \end{aligned} \quad (25)$$

Propagation degree of the performance attribute is calculated using formula (14).

The influence of active transformation on propagation properties can be measured by the degree of propagation. Active transformation will cause several propagation transformations because of the correlation between exhaust and the intake pressure. The degree of propagation is also a measure to measure the degree of the influence of several propagations taking place in a sequence.

Six transformation programs are generated by analyzing the most similar product LG-6.3/10 in which noise, intake pressure, weight, and exhaust are identified as the propagation properties. Then the six programs are classified using the method discussed in Section 4 by calculating their respective correlation functions.

Noise performance extension classification of the screw air compressor LG-6.3/10 caused by propagation transformation is as follows.

Negative quantitative:

$$\begin{aligned} E_-^4\left({}_{m_4}T_a\right) &= \left\{m_4 \mid m_4 \in M_O, y = k_4\left(m_4\right) \le 0,\right.\\ &\qquad \left. y' = k_j\left({}_{m_4}T_a m_4\right) < 0\right\},\\ E_-^4\left({}_{m_4}T_b\right) &= \left\{m_4 \mid m_4 \in M_O, y = k_4\left(m_4\right) \le 0,\right.\\ &\qquad \left. y' = k_j\left({}_{m_4}T_b m_4\right) < 0\right\},\\ E_-^4\left({}_{m_4}T_e\right) &= \left\{m_4 \mid m_4 \in M_O, y = k_4\left(m_4\right) \le 0,\right.\\ &\qquad \left. y' = k_j\left({}_{m_4}T_e m_4\right) < 0\right\},\\ E_-^4\left({}_{m_4}T_f\right) &= \left\{m_4 \mid m_4 \in M_O, y = k_4\left(m_4\right) \le 0,\right.\\ &\qquad \left. y' = k_j\left({}_{m_4}T_f m_4\right) < 0\right\}. \end{aligned} \tag{26}$$

Positive qualitative:

$$\begin{aligned} \dot{E}_+^4\left({}_{m_4}T_c\right) &= \left\{m_4 \mid m_4 \in M_O, y = k_4\left(m_4\right) \le 0,\right.\\ &\qquad \left. y' = k_j\left({}_{m_4}T_c m_4\right) > 0\right\},\\ \dot{E}_+^4\left({}_{m_4}T_d\right) &= \left\{m_4 \mid m_4 \in M_O, y = k_4\left(m_4\right) \le 0,\right.\\ &\qquad \left. y' = k_j\left({}_{m_4}T_d m_4\right) > 0\right\}. \end{aligned} \tag{27}$$

Weight performance extension classification of the screw air compressor LG-6.3/10 caused by propagation transformation is as follows.

Positive quantitative:

$$\begin{aligned} E_+^5\left({}_{m_5}T_a\right) &= \left\{m_5 \mid m_5 \in M_O, y = k_5\left(m_5\right) > 0,\right.\\ &\qquad \left. y' = k_5\left({}_{m_5}T_a m_5\right) > 0\right\},\\ E_+^5\left({}_{m_5}T_c\right) &= \left\{m_5 \mid m_5 \in M_O, y = k_5\left(m_5\right) > 0,\right.\\ &\qquad \left. y' = k_5\left({}_{m_5}T_c m_5\right) > 0\right\},\\ E_+^5\left({}_{m_5}T_e\right) &= \left\{m_5 \mid m_5 \in M_O, y = k_5\left(m_5\right) > 0,\right.\\ &\qquad \left. y' = k_5\left({}_{m_5}T_e m_5\right) > 0\right\},\\ E_+^5\left({}_{m_5}T_f\right) &= \left\{m_5 \mid m_5 \in M_O, y = k_5\left(m_5\right) > 0,\right.\\ &\qquad \left. y' = k_5\left({}_{m_5}T_f m_5\right) > 0\right\}. \end{aligned} \tag{28}$$

Negative qualitative:

$$\begin{aligned} \dot{E}_-^5\left({}_{m_5}T_b\right) &= \left\{m_5 \mid m_5 \in M_O, y = k_5\left(m_5\right) \ge 0,\right.\\ &\qquad \left. y' = k_5\left({}_{m_5}T_b m_5\right) < 0\right\},\\ \dot{E}_-^5\left({}_{m_5}T_d\right) &= \left\{m_5 \mid m_5 \in M_O, y = k_5\left(m_5\right) \ge 0,\right.\\ &\qquad \left. y' = k_5\left({}_{m_5}T_d m_5\right) < 0\right\}. \end{aligned} \tag{29}$$

Because the intake pressure is changed due to the structure change, exhaust is changed as well. Thus parameters about the exhaust of LG-6.3/10 also change due to the propagation transformation. This situation of having two propagations is termed quadratic propagation. The extension classification caused by multiple propagations is as follows.

Positive quantitative:

$$\begin{aligned} &E_+^1\left({}_{m_8}T_a \Longrightarrow {}_{m_1}T_{m_8}\right)\\ &\quad = \left\{m_1 \mid m_1 \in M_O, y = k_1\left(m_1\right) > 0,\right.\\ &\qquad \left. y' = k_1\left(\left({}_{m_8}T_a \Longrightarrow {}_{m_1}T_{m_8}\right)m_1\right) > 0\right\},\\ &E_+^1\left({}_{m_8}T_b \Longrightarrow {}_{m_1}T_{m_8}\right)\\ &\quad = \left\{m_1 \mid m_1 \in M_O, y = k_1\left(m_1\right) > 0,\right.\\ &\qquad \left. y' = k_1\left(\left({}_{m_8}T_b \Longrightarrow {}_{m_1}T_{m_8}\right)m_1\right) > 0\right\},\\ &E_+^1\left({}_{m_8}T_c \Longrightarrow {}_{m_1}T_{m_8}\right)\\ &\quad = \left\{m_1 \mid m_1 \in M_O, y = k_1\left(m_1\right) > 0,\right.\\ &\qquad \left. y' = k_1\left(\left({}_{m_8}T_c \Longrightarrow {}_{m_1}T_{m_8}\right)m_1\right) > 0\right\},\\ &E_+^1\left({}_{m_8}T_e \Longrightarrow {}_{m_1}T_{m_8}\right)\\ &\quad = \left\{m_1 \mid m_1 \in M_O, y = k_1\left(m_1\right) > 0,\right.\\ &\qquad \left. y' = k_1\left(\left({}_{m_8}T_e \Longrightarrow {}_{m_1}T_{m_8}\right)m_1\right) > 0\right\}, \end{aligned}$$

$$E_{+}^{1}\left({}_{m_8}T_f \Longrightarrow {}_{m_1}T_{m_8}\right) = \left\{m_1 \mid m_1 \in M_O, y = k_1\left(m_1\right) > 0, \; y' = k_1\left(\left({}_{m_8}T_f \Longrightarrow {}_{m_1}T_{m_8}\right)m_1\right) > 0\right\}. \quad (30)$$

Negative qualitative:

$$\dot{E}_{-}^{1}\left({}_{m_8}T_d \Longrightarrow {}_{m_1}T_{m_8}\right) = \left\{m_1 \mid m_1 \in M_O, y = k_1\left(m_1\right) \geq 0, \; y' = k_1\left(\left({}_{m_8}T_d \Longrightarrow {}_{m_1}T_{m_8}\right)m_1\right) < 0\right\}. \quad (31)$$

Transformation programs are got by analyzing multiple active transformations and it is described as $(l_1^3 \wedge l_2 \wedge l_3^1 \wedge l_4^1 \wedge l_5^1 \wedge l_6^1 \wedge l_7^1 \wedge l_8^1 \wedge l'')$. Changes in the noise attribute are positive qualitative, changes in the weight attribute are positive quantitative, and changes in the exhaust attribute are positive quantitative. Propagation knowledge extracted from the active transformation process is described as follows:

$$\left(c = T_4 \wedge T_1 \wedge T_1 \wedge T_1 \wedge T_1 \wedge T_2 \wedge T_2 \wedge T_1 \wedge T_3\right) \Longrightarrow \left(\left({}_{m_8}T_c \Longrightarrow {}_{m_1}T_{m_8}\right) \wedge {}_{m_4}T_c \wedge {}_{m_5}T_c\right) \Longrightarrow K\left(P\right) > 0. \quad (32)$$

(4) *Simulation and Verification.* In this paper, Virtual.Lab Rev10 is used to verify if the intake expanded muffler, after changes and optimization on its material and structure, can meet customers' requirements on the noise performance.

(1) 3D picture of expanded muffler after changes and optimization is shown in Figure 4. The simplified discrete solid model of the expanded muffler computational domain after transformation and optimization is shown in Figure 5.
(2) The hypermesh is used to perform mesh division on the discrete solid model of the expanded muffler computational domain, and the resultant meshes are saved in the certain documents (as .bdf). These documents are imported into the Acoustics → AHB model of Virtual.Lab Rev10. The picture of the sound pressure cloud after calculating and transmission loss of muffler are shown in Figures 6 and 7.

Virtual.Lab Rev10 is used to simulate the transmission loss of the muffler after transformation to get the transmission loss curve at different frequencies. It is shown that the schemes after transformations meet the requirement of the low-frequency noise. It also complies with the trend of the extension configuration design elements discussed above.

7. Implementation of a Prototype System

A prototype system for the configuration design and conflict resolution for large screw air compressor has been developed based on a previous ET-based design system V1.0. The graphical user interface of the prototype system is shown in Figure 8, and graphical user interface for conflict resolution design system is shown in Figure 9.

The prototype system includes

(1) the module for degree-of-matching calculation between customers' performance requirements and the performance attribute values of a specific product: the graphical user interface in this module is used to explain the process as well as the operations involved in this module; the same idea is used for the explanation of other modules as well;
(2) the conflict resolution module which involves the transformations of performance attributes based on propagation analysis;
(3) the module for extracting knowledge from the propagation process;
(4) the module for outputting generated design schemes.

8. Conclusions and Future Work

The description of performance requirements and the resolution of conflicts caused by different requirements hold to key to effectively meeting new market needs. In this paper, a method for conflict resolution in the PDD is proposed based on the transformation of performance attributes and the propagation of changes. The degree of how a product meets a specific performance requirement is evaluated using a measure of similarity. To fit with the purpose of retrieving product cases from a case base, the traditional distance measure in the Extension Theory is improved in terms of both the left-side distance and the right-side distance representations. In addition, the correlation between product performance attributes and product structure parameters is established to identify the methods for performing transformations on the current design space and use change propagation to coordinate conflicts. On this basis, the method for coordinating conflicts based on the Extension Theory is devised and the method for mining propagation knowledge is developed. These methods have been evaluated in a screw air compressor design problem and implemented in a prototype system for conflict resolution for PDD.

It is shown in the evaluation that the improved distance representation achieves improved retrieval precision. The proposed conflict resolution method is feasible and implementable. As shown in the case study, the method effectively performs several transformations during the coordination of conflict for the screw air compressor and utilizes the propagation of design changes to resolve conflicts and thus improve overall performance. It also shows that the Extension Theory provides effective formal model for the resolving of conflict problems especially in the design domain where problems are highly coupled and multidimensional. This work is still at an early stage and a lot of work needs to be done in the future. Firstly, we will improve the case base and include more performance attributes in each case. Secondly, more complicated design problems will be analyzed and the proposed method will be used in these problems. Thirdly, the functionality of the prototype system will be improved.

Conflict of Interests

The authors declare that they have no conflict of interests regarding the publication of this paper.

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