Product Requirement Modeling and Optimization Method based on Product Configuration Design

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Abstract

Product requirement modeling is a process that the product requirement information is collected, analyzed, structured and converted to the design specification, it is the determinant of the ability to quickly respond to the diverse requirements of customers. This paper presents a product requirement modeling method based on configuration design, which uses “tabular layouts of article characteristics” (SML) technology to conduct the formal expression of product requirement information element. The function structure model and its optimization algorithm are proposed. Enterprises can use the model to interact with customers about requirements and obtain the model which can be manufactured. The customer individual requirements can be satisfied according to the mapping rules of models. Finally, an example of enterprise application is given to illustrate practical application of the research.

Keywords: Product requirement modeling; Configuration design; Function structure model; Customer requirement

1. Introduction

As the development of computer technology and the increasing fierce in market competition, customer requirements are becoming more and more diverse and personalized. The enterprises gradually focus competition on how to increase external variety of products to meet customers’ individual requirements under time and cost constraints by decreasing the internal variety of products, thus realize the maximization of enterprise profit. It also forces the production mode transform from the original mass production methods to mass customization mode. However, the difference of semantics and terminology makes it difficult to map the product requirement information from customers to enterprises designers in mass customization mode, as they expressing product requirement information based on different area knowledge. While product requirement information is short of clear architecture, the relationships between different variables of product architecture are difficult to express formally, so do the relationships between product requirements variables and design parameters [1]. How to obtain the customers’ individual requirements through requirements interaction and produce customized products under the current production conditions and cost constraints has become a bottleneck problem which needs to be solved.

Literature [2] proposes an ontology-based requirements elicitation method from the perspective of software implementation. This method makes enterprise ontology and domain ontology as the basic clues of requirements elicitation, Literature [3] adopts the product requirements topology to conduct the acquisition and expansion of requirement information for product life cycle. As a result the systematization and efficiency of requirements acquisition is improved. Literature [4] has a discussion on how to integrate requirement information acquired in the product design process to ensure the consistency of requirement information from the perspective of product design. Literature [5] proposes the customer requirements of coach products on knowledge
representation and construction methods based on ontology. The customer requirements utility data model and a two-step conversion method is proposed. Literature [6] discusses some of the misconceptions that exist in industries regarding requirements engineering and how user needs typically slip through the cracks under the name of “nonfunctional requirements”. Literature [7] analyzed requirement design and its function in concurrent design. Then the method for the market's information acquisition and handling was discussed. As a result, the function of the product was refined. The modeling methods above all assume that the product development and design start from scratch. In fact, however, during the product configuration design process of mass customization, manufacturing model of configurable products are usually designed by mapping historical data through product configuration design and parametric variant design based on the designers’ interaction with the customers' requirements. This paper presents a product requirement modeling method of configuration design, which uses SML technology to conduct the formal expression of product requirement information element. It proposes the product FS model and its optimization algorithm on the basis of above. Enterprises can use the model to interact with customers about requirements and obtain the model which can be manufactured and meet customers’ individual requirements gradually according to the mapping rules of models.

2. Definition of product requirement information element based on SML technology

SML refers to the characterization of properties of products (including parts, components), such as geometry, features, supplements, algorithms, classifications and properties, and the form of fixed-format tables reflecting the information collection of objects. It defines the decisive characteristic of an object through a way that can be characterized and distinguished from the object group and also the representation format of characteristic data. Description of the products, components and parts through these characteristics makes it easy for characteristic data of products to communicate between different systems. In the production mode of mass customization, basing on requirements analysis and forecasting of future requirements and aiming at a certain customer base to use a series of SML to describe the connection among appearance, function and structure size of configurable products. Furthermore, through SML instantiated, manufacturing models are derived to meet customer’s individual requirements according to the configuration rules.

Product requirement information element of configuration design-oriented refers to using SML technology to express the basic unit of product requirements constituting the target feature items, which provides a basic method for acquisition, description, management and use of product requirement information in requirement modeling process. The formal expression of product requirement information element of configuration design-oriented is using SML technology to express the basic unit of product requirements constituting the target feature items, as shown in formula (1):

\[ T\_Meta = \{T\_id, T\_datatype, T\_conts, T\_domains, T\_Metatype\} \] (1)

Where \( T\_Meta \) is product requirement information element; \( T\_id \) is a unique identification of product requirement information element. There are two types of configurable product requirement information element. One is associated with geometry, materials, functions, such as color, texture, etc. and the other is related to object structure and assembly relations. \( T\_datatype \) is the attribute value type of product requirement information element, such as integers, real numbers, character, boolean, etc; \( T\_conts \) is the value constraint of the attribute value of product requirement information element. Among it, option means not choosing or selecting a value from the range, and the compulsory is to enter a value or select a value within an interval range; \( T\_domains \) is the range of attribute value of product requirement information element.

3. Configuration-oriented design of Product Function and Structure Model (PFSM)

Configuration-oriented design of product function and structure model (PFSM) are based on formalized express of product requirement information element of SML technology, adjusting attribute value of requirement information element and constraints to meet customers’ requirements for personalized expression of functional structure model. Nodes in all levels of PFSM are expressed by Function and Structure units. In PFSM, each node, namely Function and Structure units, has the ability to represent multiple instances of components, which can be formally expressed as formula (2):

\[ \text{PFSM\_Unit=}\{\text{FS\_id, FS\_option, FS\_type, Mult}\_Meta, \text{is\_decomposed}\} \] (2)

Where \( \text{PFSM\_Unit} \) is FS units of PFSM, \( \text{FS\_id} \) is the unique identification of the FS unit, \( \text{FS\_option} \) is the selecting characteristic of FS units. When \( \text{FS\_option} = 1 \), it means that the FS unit is mandatory unit of configured products. When \( \text{FS\_option} = 0 \), it means that the FS unit is optional unit of configured products. All mandatory units are consist of standard configuration of configured product and all the optional units are consist of matching function and optional configuration of configured products. \( \text{FS\_Type} \) is the type of FS units. FS units are divided into two categories. One is the standard FS unit (\( \text{FS\_Type} = 0 \)), which once selected, no other FS unit information is needed to be manufactured and designed, the other is parameterized configuration unit (\( \text{FS\_Type} = 1 \)), which has some parameters that must be determined after determination of a certain characteristic values of other FS units or in designing process. \( \text{Mult}\_Meta \) indicates that the property value of the FS units can be described by units of other various SML. \( \text{is\_decomposed} \) is the property that if the FS units are decomposable, it can be divided into complex FS unit and element FS unit according to the FS unit which can be further decomposed or not. Element FS unit is in the leaf node location and couldn’t be decomposed in PFSM. The complex power structure unit refers to \( \text{PFSM\_Unit} \) in the middle layers of the hierarchy tree of PFSM. According to functional requirements, it can be
further decomposed into the next level, namely, if \( Is_{\_decomposed} = 1 \), it is a complex FS unit; if \( Is_{\_decomposed} = 0 \), it is an element FS unit.

Table 1. PFSM UNIT.

<table>
<thead>
<tr>
<th>Fs_ids</th>
<th>Air_compressor _ _ Door</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fs_Type</td>
<td>0 (standard configuration)</td>
</tr>
<tr>
<td>Is_Decompose</td>
<td>1 (configuration unit)</td>
</tr>
<tr>
<td>T_Widht</td>
<td>Select(1500,2600)</td>
</tr>
<tr>
<td>T_Thickness</td>
<td>Select(4,8,12)</td>
</tr>
<tr>
<td>T_Material</td>
<td>Option(stainless steel, Aluminium alloy plate)</td>
</tr>
<tr>
<td>T_Cost</td>
<td>Value</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Table 1 is a FS unit of an air compressor door, showing all kinds of SML unit \( T_{meta} \) which constitute the air compressor door and constraint information between the car units.

In the FS model for configuration design, constraint relationship can be expressed as:

1) Constraint relation between SML in FS unit can be expressed as the relation between the export characteristic unit and the basic characteristics unit of the FS unit. For example, the relationship between costs and other units can be expressed as formula (3):

\[
T_{cost} = F(T_{width}, T_{thickness}, T_{height}, T_{material}, T_{color})
\]

2) Constraint relation between the FS units. This is a global constraint relationship. This global constraint relationship can be expressed formally as the incompatible relation and concurrent relation between configuration units while the concurrent relation can also be divided into if-then relation and none if-then relation. And it can be divided into parent-child relation and adjacency relation from the perspective of hierarchy of configuration model as well.

3) Constraint relation between one FS unit as a whole and a certain characteristic of another FS unit.

4) Constraint relation between a certain characteristic of one FS unit and another FS unit. This constraint relation can be divided into three types. First, some type can be described as \( >, <, =, \neq \) etc. Formally, this kind of constraint relation has an effect on checking the confidence of product configuration results. Second, some type can be expressed formally as if …then…. This kind of constraint relation is expressed as condition select judgment of FS units in configuration process. Third, some structure can be expressed as the constraint relation between structural characteristics of one FS unit and features characteristics of another FS unit, which is shown in formula (4):

\[
T_{Meta_{select}} \times (T_{Meta_{function}} \times T_{Meta_{function}} \times \ldots \times T_{Meta_{function}})
\]

The constraint relations above in the requirements interaction process for configuration design could be expressed as derive the property value of feature characteristic of the target FS unit on the basis of the PFSM constraint relation according to the feature characteristic parameters input by customers and other relative FS unit. This kind of constraint relation can be expressed by function or assembly constraints between FS units. As a nonlinear relation, it needs to be achieved by the way of human-computer interaction and drive the product parametric design and optimization design deformation when it’s necessary.

4. Product FS model optimization algorithm for configuration design

Since the development of the product that can be configured expands at a predetermined mode of production, the process of customer requirements function input in PFSM is actually a process of instantiating the SML functional unit which constitutes a functional structure model, that is:

\[
FR = A \cdot T_{Meta_{function}}
\]

Where \( T_{Meta_{function}} \) is the feature unit matrix related to product functional requirements, \( [A] \) means customer requirements matrix.

According to formula (2), the structure properties of products which can be configured are expressed by the structural characteristics of things in the product FS model. So the structural parameters, which decide SML product FS model unit can be expressed as follows:

\[
DP = B \cdot T_{Meta_{function}}
\]

Where \( T_{Meta_{function}} \) is the feature unit matrix related to the structural parameters of functional structure model, while \( [B] \) is the design matrix. Thus, the mapping relation between customers’ functional requirements and design parameters of configuration unit can be expressed through feature units of functional structure model.

Layer by layer decomposition strategy is adopted from the top-down based on MC for the process of product configure design to the leaf nodes of the functional configuration model. In the process of decomposition and mapping, according to the independence principle in axiomatic design theory [8] proposed by Suh etc., Concentration factors of each function requirements decomposed from configure product should be independent and non-coupling or quasi-coupled mapping are adopted between set of functional requirements\([FR]\) and design parameters\([DP]\). Therefore, the customer requirements matrix \([A]\) and design matrix \([B]\) are expressed correspondingly as diagonal matrix. The \([DP]\) could be triangular matrix which can transform correspondingly to diagonal matrix:

\[
[A]_{n \times n} = \begin{bmatrix}
A_{11} & 0 & \ldots & 0 & \ldots & 0 \\
0 & A_{22} & \ldots & 0 & \ldots & 0 \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & A_{nn} & \ldots & 0 \\
0 & 0 & \ldots & 0 & \ldots & A_{nn} \\
\end{bmatrix} \quad \quad [B]_{n \times n} = \begin{bmatrix}
B_{11} & 0 & \ldots & 0 & \ldots & 0 \\
0 & B_{22} & 0 & \ldots & 0 & \ldots \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & B_{nn} & 0 & \ldots \\
0 & 0 & \ldots & 0 & \ldots & B_{nn} \\
\end{bmatrix}
\]
The same SML unit which is taken from $T_{\_Metafunction}$ and $T_{\_Metastructure}$ forms $T_{\_Metacommon}$, then formula (5) and formula (6) are transformed as follows:

$$\begin{bmatrix}
FR_{\_common} \\
DP_{\_common}
\end{bmatrix} = 
\begin{bmatrix}
A_{\_common} & 0 \\
0 & A_{\_common}
\end{bmatrix}
\begin{bmatrix}
T_{\_Metacommon} \\
T_{\_Metacommon}
\end{bmatrix}
$$

(8)

$$\begin{bmatrix}
DP_{\_common} \\
DP_{\_common}
\end{bmatrix} = 
\begin{bmatrix}
B_{\_common} & 0 \\
0 & B_{\_common}
\end{bmatrix}
\begin{bmatrix}
T_{\_Metacommon} \\
T_{\_Metacommon}
\end{bmatrix}
$$

(9)

According to Formula (8) and Formula (9), it can be derived as follows:

$$DP_{\_common} = B_{\_common} \cdot A^{-1}_{\_common} \cdot FR_{\_common}$$

(10)

Moreover, the mapping between the design parameters $[DP]$ of functional structural units and its practical projects $[PP]$ can be expressed as follows:

$$PP = M \cdot DP$$

(11)

Where $[M]$ means the mapping matrix from physical domain to process domain.

It can be derived from formula (10) and formula (11):

$$PP_{\_common} = M \cdot B_{\_common} \cdot A^{-1}_{\_common} \cdot FR_{\_common}$$

(12)

While customers propose a new functional requirements. Considering the independence of functional requirements, the customer requirements coefficient matrix $[C]$ can be expressed as follows:

$$[C] = 
\begin{bmatrix}
C_{11} & 0 & \ldots & 0 \\
0 & C_{22} & \ldots & 0 \\
\ldots & \ldots & \ldots & \ldots \\
0 & 0 & \ldots & C_{nn}
\end{bmatrix}$$

(13)

The result of customers’ requirements interaction is that the customers and designers obtain a set of physical solution which meets:

$$PP_{\_common} = M \cdot B_{\_common} \cdot A^{-1}_{\_common} \cdot C^{-1} \cdot FR_{\_common}$$

(14)

It could be decoupled or redesigned as the $FR_{\_common}$ and $DP_{\_common}$ are based on different SML units and there is a coupling relation between PFSM units. Correspondingly, $PP_{\_common}$ must be solved by designers based on $PP_{\_common}$ according to the functional requirements of customers.

In the Product requirement modeling process for configuration design, optimal solutions could be obtained by adjusting matrix $C$ and SML unit matrix $T_{\_Meta}$. If the SML unit, which already has a FS model, meets customers’ needs, the optimal solution of configurable products could be gotten by maintaining customers’ functional requirements coefficient matrix $C$ according to the configuration policy of global priority and partial adjustment. If the FS model’s SML unit can’t express the requirements of customers totally, however, designers must get the FS model decoupling and optimizing. The optimal algorithm is shown as follows:

1) Making it convey the functional requirements of customers totally by adjusting the SML unit of FS model.
2) Decreasing the SML units as far as possible and reflect the geometry and topology relation of FS model node by exporting features.
3) Satisfying $T_{\_Metafunction} = T_{\_Metastructure} = T_{\_Metacommon} = T_{\_Meta}$ as far as possible, thus, $B_{common} = B$, $A_{common} = A$, $C_{common} = C$, $FR_{common} = FR$, formula (14) is transformed to:

$$PP = M \cdot B \cdot A^{-1} \cdot C^{-1} \cdot FR$$

(15)

Thereby the part of manual configuration can be reduced. While the model can fully express the customers’ functional requirements. Then the manufacturing model is obtained, which satisfies the customers requirements and the mapping relation between physical domain and process domain.

5. Product requirement modeling process based on PFSM

Product requirement modeling process based on PFSM is expressed as a series of interrelated activities. From customers’ pressing functional requirements to obtain the product model that can be manufactured, solutions of the problem are complex [9]. The specific steps are as follows:

Step 1: Customer requirement information is analyzed and the future requirements are forecasted according to the customer base location. Then PFSM is built and SML unit of PFSM is defined. Thus, the system generates product requirements specification (PRS) automatically. We can get customer requirements coefficient matrix $[C]$ by instantiated description on customer requirements.

Step 2: When customers propose their personal requirements (non-standard products), the designers would assess relative SML unit in PRS and its constraints. If the PFSM could satisfy the customers’ personal requirements, it will go to Step 3. On the contrary, designers in enterprises perform maintenance on PFSM under the constraints of time, technology and cost. If there is a PFSM UNIT coupling in non-standard products, down-coupling and decoupling design would be performed. If the customer requirements do not agree with PRS instantiated through consultation, it will go to Step 6, otherwise, Step 3.

Step 3: Customers define the functional requirements coefficient matrix $[C]$ according to the PRS specification. Enterprises take it as an important basis of product design, manufacture and project.

Step 4: According to PRS, the FS unit layer by layer is traversed starting from the root.

If the PFSM UNIT[i] ($0 < i \leq n$) in PFSM meets $T_{\_Metafunction[i]} = T_{\_Metastructure} = T_{\_Metacommon}$, the system takes its auto-configuration, obtaining DP corresponding to the cell. On the contrary, PFSM and conduct manual configuration is decoupled according to matrix$[C]$. 

\[\text{PP} = \mathbf{P} \cdot \mathbf{B} \cdot \mathbf{A}^{-1} \cdot \mathbf{C}^{-1} \cdot \mathbf{FR} \]
associated with parent node and the adjacent node property value.

Step 5: While \( i = i + 1 \), information about production cycle and manufacturing costs of the manufactured model could be obtained according to relative mapping relation between physical domain and process domain. If these information meets the PFSM global constraints, it will go to Step 6, on the contrary, return to Step2. Then we have a loop processing until it satisfies the global constraints of FS model and customer functional requirements.

6. Case study and enterprise application

The components of air compressor product have been taken the frequency analysis in the system, which is the basis of modular, standardization, normalized and parameterized design for product components. Besides, the system gets the product requirement information element for configuration design and establishing FFSM according to customer requirements analysis. The system includes SML data maintenance, property maintenance, attribute formula definition, constraint rules management, function structure definition and configuration template management.

The reasoning technology and fuzzy pattern recognition technology based on instances are adopted in the system. According to the main requirements parameters input by customers, one or a group of the most similar instances are gotten. Meanwhile, the system interacts with the customer needs according to the FFSM model and chooses the best instance which can satisfy the customer requirements.

7. Conclusion

This paper proposed a product requirement modeling and optimization method based on product configuration design. By using this model, the problem of the interactive semantic consistency between customers and designers is solved. The mapping relation between customers’ functional requirements and product design parameters is also expressed in the model, which helps provide the tools for enterprises to obtain the customer requirement information accurately and rapidly.

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References