Extension Method in Case-Based Reasoning and its Application in Artillery System Design

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Abstract. Case-Based Reasoning (CBR) is a method of designing new product configurations based on previous design case matching. Over the last couple of decades, CBR has grown from a relatively isolated research area to a comprehensive and multi-field one. Extenics is one of fields combined with it. The representation model and extension distance theory in Extenics are surveyed. Based on dependence function, an improved comprehensive evaluation of configuration schemes of a complex modularized product is proposed, considering the interface matching problem that may occur between different components. To illustrate the validity and feasibility of our method, a design case of artillery system is described. The result shows that our evaluation method can better adapt to engineering practice and provide effective and reasonable matching results.

1. Introduction
In order to solve the design problems in mechanical engineering, it often requires a good deal of design experience, or relies on quantities of information, which will take designers lots of time to do researches, attend meetings and reach consensuses. Case-based reasoning (CBR), has proposed a method to find similar pre-existing solutions, and reuse them in new design problems. It is also capable of sustained self-learning, implemented by retaining the new, adapted case in databases and making it available for future cases [1]. To realize the CBR procedure, authors have generalized it as the following phases: representation, retrieval, reuse, revision and retaining [2].

During the implementation process of CBR, the representation and retrieval of cases are always the central task. Firstly, representation of domain knowledge in mechanical engineering varies from others in that the data format is not uniform and the diverse kinds of information have enhanced the difficulty in building a structured representation system. In order to resolve the deficiency of past establishment methods of case bases, the matter-element and extension set theory of Extenics is introduced. In this theory, a matter-element model, which is an expression of a matter, its characteristics and their measures, is capable to describe the diverse objective matters qualitatively and quantitatively; while an extension set is developed on the basis of classical set and fuzzy set, aiming to describe how a matter-element possesses a property [3]. Secondly, a modified similarity model on the basis of extension distance, as well as an improved dependence function based on similarity calculation, is presented, aiming to better adapt to the expression of the characteristics in engineering field and improve the efficiency and accuracy in the process of case retrieval.

As to the artillery weapon system, most of the design cases are based on modular design, rather than designing from scratch. Besides, functions of artillery are deemed to be implemented by subsystems or modules of it. Due to the convergence and modularity of artillery weapon system, a configura-
tion design method based on extension case-based reasoning is proposed. This paper presents an artillery design case as an example to demonstrate the method mentioned above.

2. The Extension Methods in Cbr

Before the retrieval process, pivotal components serving as case indices for the design problem, and characteristic weights utilized in similarity calculation, need to be determined, which requires joint efforts of knowledge engineers and domain experts. The indexed cases are diverged and reorganized to obtain a preliminary product configuration scheme. Through the determination of overall similarity, a list of cases best matching the new design requirement can be obtained, ranked in order. They are considered as candidates for solving the given design problem. Eventually the selected scheme can be retained in the case base, available for future design work.

2.1 Matter Element and Matter-Element Extension Set

The matter-element theory, from Extenics, introduces a three-tuple model made up of matter, characteristics and their corresponding measures, which takes not only quality, but also quantity into account. According to Extenics, the multi-dimensional matter-element model of a case is defined as follows [4]:

$$ R = \begin{bmatrix} N & c_1 & v_1 \\ c_2 & v_2 \\ \vdots & \vdots \\ c_n & v_n \end{bmatrix} = (N, C, V) $$

where $N$, the matter’s name; $c$, its characteristic; $v$, the measure about $c$. $C$ is a finite set of characteristics of the matter and $V$ is a set of their measures. Designation of $N$ can be used for indexing of cases. Set $C$ and set $V$ are respectively the qualitative and quantitative representation of domain knowledge.

The matter-element extension set is used to describe the relationship between the change of the degree of a matter possessing a certain property and the change of the matter [4]. Down to the field of CBR, it can reflect the matching degree of case characteristics to design requirements. Given case field $U$ and extension set

$$ \tilde{A} = \{(v_1, v_2, \ldots, v_n, y) | \forall y \in I, y = K(v_1, v_2, \ldots, v_n)\} $$

we have the matter-element extension set

$$ \tilde{A}(R) = \{(R, y) | R = (N, C, V), N \in U, y = K(R) = K(v_1, v_2, \ldots, v_n)\} $$

where $K$ is a mapping from the field $U$ to real number field $I$. $K(R)$ is the dependence function, which is a quantitative expression of a certain property of the element $R$ in the set.

By applying the matter element and matter-element extension set model of Extenics in CBR, the cases and problems are described both qualitatively and quantitatively, so that they can be dynamically related, increasing the flexibility of knowledge reuse.

2.2 The Extensible Property of Matter Elements

In Extenics, extensibility mainly refers to the possibility of changes in matters. In terms of case-based reasoning, the meaning can be summarized as the possibility of a certain transformation conducted on the cases in order to meet the design requirements. The extensibility mainly includes four aspects:

a) Divergence and opening-up: Divergence means that a matter usually owns multiple characteristics, and a characteristic is usually owned by multiple matters. While opening-up property refers to the composability and decomposability of matters. In CBR, it is common to derive multiple matter elements according to the principle of similarity matching from different cases, and form product scheme candidates that may satisfy the design requirements by decomposing and reorganizing.

b) Implication: In product design, implication means the implementation of the upper-level functions is achieved through its sub-functions, that is, there is a natural implication between the components used to implement the functions in the product.
c) Correlation: Different matter elements may have a correlative relationship. When calculating the similarity between cases and the design requirement, the interface relationship inside the product system should be considered and included in the overall evaluation of the configuration scheme.

2.3 Dependence Function
On the basis of extension set, Extenics presents the concept of dependence function to quantitatively describe the degree elements in a set are having a certain property as well as its change. The existing calculation approaches \[4\][6][7] are usually general ones, which do not completely fit in with similarity calculation in engineering situations. Zhao et al. \[5\] introduced a calculation model built on the basis of extension distance, and applied it to a chain saw design case, which has proved it suitable for practical engineering problems. This paper further improves their works and proposes an overall evaluation method of case configuration scheme based on the concept of dependence function.

2.3.1 Local similarity calculation. Since most of engineering parameters are of quantitative nature, the measure of elements in C can be either a value or an interval, which causes the similarity calculation to be under three circumstances:

a) Numeric to numeric: When \(v_i\) and desired \(v_0\) from the design requirement are both numeric, normalize the absolute distance between them to obtain the relative distance \(d_i\), and the similarity between \(v_i\) and \(v_0\) is

\[
s_i = 1 - d_i = 1 - \frac{|v_i - v_0|}{\max(v_i) - \min(v_i)}
\]

(1)

where \(\max(v_i)\) and \(\min(v_i)\) are the maximum and minimum of all possible values of the \(i\)th characteristic in \(C\) within the case base. It’s obvious that \(s_i\) is in \([0, 1]\), assured by the normalization of distance \(d_i\).

b) Numeric to interval: When \(v_i\) is numeric while \(v_0\) is an interval \([a, b]\), the similarity \(s_i\) is

\[
s_i = \begin{cases} 
1 - \frac{|v_i - a + b|}{\max(v_i) - \min(v_i)}, & v_i \notin [a, b] \\
1, & v_i \in [a, b]
\end{cases}
\]

(2)

c) Interval to interval: Assume that \(v_i\) is the interval \([c, d]\) and \(v_0\) is \([a, b]\), their distance is defined as:

\[
s_i = 1 - \frac{|a + b - c + d|}{2} - \frac{|b - a - d - c|}{2}
\]

\[
\max(v_i) - \min(v_i)
\]

(3)

2.3.2 Improved dependence function calculation based on overall similarity. According to the implication principle, whether a matter element of product case meets the design requirements can be known by the evaluation of its subsystems. Assuming product case \(R\) contains component \(R_j\), the matching degree between \(R_j\) and the design requirement can be calculated via the characteristics and their values in the set \(V_j\). Usually, the characteristic set \(C_j\) has a weighted structure. The distribution can be accomplished by the collection of domain expertise, or the utilization of analytic hierarchy process. Assuming that \(R_j\) has \(n\) characteristics, and taking the weights \(w_i\) into account, the overall similarity between \(R_j\) and the design requirement is defined as:

\[
S_j = \sum_{i=1}^{n} w_i s_i
\]

(4)

Another problem existing in the process is the interface matching between components, or modules. In practice, a configuration scheme with highest value of overall similarity is not necessarily the opti-
mum solution to the problem, due to the incompatibility between different components. Addressing this issue, an evaluation method of configuration schemes was proposed by Zhao et al. [5], which has taken into consideration the interface matching problem. Assume that the jth component has l interface relations with other different components, denoted as \( d_k \), where \( k=1,2,\ldots,l \). The interface distance value can be obtained utilizing the same calculation method based on extension distance. Then the improved dependence function derived from the overall similarity calculation is

\[
K(R) = \sum_{j=1}^{m} \sum_{l=1}^{k} S_{j} \cdot D_{j}, \quad \text{where} \quad D_{j} = \sum_{l=1}^{m} d_{l}
\]

In a product configuration design based on extension CBR, we use \( K(R) \) as the indicator to comprehensively evaluate the configuration schemes. Normally the cases are ranked and screened according to \( K \) value, or selected via a threshold of \( K \). The candidate schemes can be utilized for further modification design.

2.4 The Concept and Method of Extension Transformation

Through the introduction of theory of matter element and extension set, the degree of matter transformation can be expressed. The transformation process is mainly embodied in the change of characteristics and their values [3]. The theoretical basis of the process is the extensible property of matter elements, and the means of implementation is extension transformation. Zhao et al. [8] gives the transformation rules in a product configuration design. Combined with the extension set theory, the following generalization is made: denoting transformation \( T \) as the extension transformation conducted on the element \( R \) in matter-element extension set, i.e.

\[
TR = R'
\]

If the transformation renders dependence function \( K(R') \) improved on the basis of the original one, that is, matter element \( R \) better satisfies the design requirement, then transformation \( T \) is considered to be reasonable. In the field of CBR, there are two main types of transformation: basic transformation and conductive transformation, which will not be elaborated in this paper.

3. Application in Artillery System Design

3.1 Design Requirement and Case Representation

To illustrate local similarity calculation, a design case of traversing mechanism is subsequently taken as an instance. Traversing mechanism is used for azimuth aiming within traverse limits, characterized primarily by azimuth laying speed, traverse range, maximum azimuth laying acceleration and so forth. The design requirement is stated in Table 1.

| Characteristic          | Weight | Value      | Target Value     |
|-------------------------|--------|------------|------------------|
| Type                    | 0.3    | Worm       | Toothed arc      |
| Drive                   | 0.2    | Hydraulic  | Electrical       |
| Laying Speed(°/s)       | 0.1    | 0.43       | 5-8              |
| Traverse Range(°)      | 0.2    | (-25,25)   | (-180,180)       |
| Acceleration(rad/s²)   | 0.1    | 0.064      | 0.1              |
| Rotary Inertia(kg·m²)  | 0.1    | 1250.5     | 25000            |

The above design problem description has indicated governing features and their desired values of a traversing mechanism. Traversing mechanism, caliber 155mm, and other governing features serve as case index for the design problem. Similar cases are indexed from the case base for decomposition and reorganization, and candidate product configuration schemes obtained. For instance, via a preliminary configuration we have product matter element.
Whether it satisfies the design requirement can be determined by the characteristics of its sub-matter-elements $R_1, R_2, \ldots, R_n$, which respectively stand for traversing mechanism, counter-recoil mechanism, etc. According to the definition of matter-element extension set and dependence function, the CBR process corresponds to generating an extension set from the case field $U$, and the dependence function of it should reach a certain threshold, i.e. $K(R) > \varepsilon$.

3.2 Evaluation of Configuration Schemes

Table 1 also presented a traversing mechanism case and their weight distribution. Numeric local similarity for a single component has been define by Eqs. (1)-(3), while the similarity between textual characteristics is determined as Boolean values. Taking into account the values of weights $w_i$, the overall similarity of can be obtained. The result and similarity degrees of other components and cases are summarized in Table 2, in which only two components, three cases are listed due to space limit. Among the candidates of barrel module, Case 1 and Case 2 have obviously a better match with the problem, which requires an autofretted type barrel, with its caliber length 50, max chamber pressure 380 MPa and chamber volume 20 dm$^3$, despite the fact that Case 3 are numerically closer to it in characteristic “caliber length”, “max chamber pressure” and “chamber volume”. Whereas these characteristics have comparatively smaller weights than the qualitative “type”, conducing to the result that the comprehensive similarity of Case 3 receives a considerable discount as a whole.

| Module Name | Characteristic | Case 1 | Case 2 | Case 3 |
|-------------|----------------|-------|-------|-------|
| Traversing Mechanism | Type | toothed arc | toothed arc | worm |
| | Drive | electrical | mechanical | hydraulic |
| | Azimuth Laying Speed (°/s) | 7 | 0.66 | 0.43 |
| | Traverse Range (°) | (-180,180) | (-22.5,22.5) | (-25,25) |
| | Max Azimuth Laying Acceleration (rad/s$^2$) | 0.085 | 0.0121 | 0.064 |
| | Rotary Inertia of Involving Part (kg·m$^2$) | 30000 | 1670 | 1250.5 |
| | Similarity | 0.969 | 0.504 | 0.247 |
| Barrel | Type | autofretted | autofretted | partially autofretted |
| | Caliber Length | 39.26 | 39.05 | 52 |
| | Max Chamber Pressure (MPa) | 380 | 305 | 370 |
| | Chamber Volume (dm$^3$) | 17.88 | 17.29 | 22 |
| | Similarity | 0.876 | 0.836 | 0.568 |

Taking the matching relations between different modules into consideration, the overall similarity of all modules of schemes with different configurations of cases and their evaluation values are presented in Table 3. Through the comparison between Scheme 1 and Scheme 2, it is easily seen that the most similar configuration scheme doesn’t necessarily possess the highest evaluation value. In other words, a simple combination of cases with highest similarities may include structural or other interference problems between different components, leading to its evaluation value possibly lower than other alternative ones. If we set the threshold of scheme evaluation value $\varepsilon$ as 9.0, a further modification work, or an adaptation of the schemes has to be conducted on the matching results. That is, to perform effective extension transformation on sub-matter-elements of Scheme 1 or Scheme 2, including conduction and other transformations, to improve $K(R)$, so that the design requirement is better satisfied.
Table 3. Configuration schemes and evaluations

| Module Name         | Scheme 1 |         | Scheme 2 |         | Scheme 3 |         |
|---------------------|----------|---------|----------|---------|----------|---------|
|                     | Conf.    | Sim.    | K        | Conf.    | Sim.    | K        |
| Traversing Mechanism| Case1    |         |          | Case1    |         | Case1    |
| Counter-recoil Mechanism | Case1   |         | Case2    |         |         |         |
| Elevating Mechanism  | Case1    |         | Case1    |         | Case1    |         |
| Balancing Mechanism  | Case1    | Case1   | Case2    | Case1    |         |         |
| Muzzle Brake         | Case1    | 9.093   | 8.211    | Case1    | 8.952   | 8.456    |
| Breechblock          | Case1    | Case2   | Case2    | Case1    |         |         |
| Gun Breech           | Case1    | Case1   | Case1    |         | Case2    |         |
| Cradle               | Case1    | Case1   | Case1    |         | Case2    |         |
| Recoil Mechanism     | Case1    | Case2   | Case2    | Case1    |         |         |

4. Conclusion

For a modular product system, especially those with long developing cycle, the application of configuration design based on CBR can meet the variable requirements of designers as well as shorten the developing period, implemented by the inheritance and adaptation of existing design cases. In a complex mechanical system, it is usually difficult to represent the design problem and cases in a well-structured data format, due to the diversity of them: qualitative or quantitative, textual or numerical, approximate or concrete and so forth. The proposed matter-element extension set representation is able to cope with the hierarchical product systems with different data formats efficiently and flexibly.

A modified evaluation method based on the concept of dependence function is proposed in order to overcome the limitations of traditional calculation methods. The method has been illustrated with application to an artillery system design case. The result shows that interface function can, to a large extent, affects the final evaluation value. Also, our comprehensive evaluation method adapts to engineering practice well and makes the CBR results more reasonable and effective. The development of such theory is a subject of future work.

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6. References

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