# Complex mechanism scheme design based on knowledge extension reuse model

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**Abstract**

Due to the multi-hierarchy, multi-attribute and creativity exist in the structure configuration process of the large-scale complex product scheme design; a reuse model for scheme design knowledge based on extension theory is presented here. The basic-element in model can unified describe the design information with the combination way on both qualitative and quantitative, the retrieval and matching of basic-element are realized by retrieval algorithm based on distance, the best reuse objects are obtained to applied to new scheme design. Finally, an illustration verifies this proposed model.

*Keywords:* Knowledge Extension Reuse, Scheme Design, Extension Theory, Artificial Design

## 1 Introduction

For large-scale and complex product scheme design in the industries such as aerospace, generating equipment, the product manufacturing mode shows single piece, small batch and large complete set, their scheme design is a complex, multi-hierarchy, multi-attribute and creative process of configuration design. Therefore, new product design usually needs the existing design schemes for reference, the design schemes and the design rules, methods and experiences in old product can be inherited and reused, and which can be applied effectively to new scheme design[1-4]. The reasonable organization and reuse of design knowledge can effectively improve the design efficiency in large-scale complex product, and the research on the reuse technology about complex product design has an important engineering application value and scientific research significance. At present, the research on knowledge reuse technology is widespread international concern[5-9]. A large number of theoretical studies and practical applications show that show that good compatibility between the knowledge models of product design and design reuse methods is the key to the product design knowledge reuse. Extenics is a new subject which studies the methods on expand possibility and innovation of things with formal model is established, the rules and methods in solving contradictory problem are researched qualitatively and quantitatively with formal tools, the process in solving problems is formally processed for corresponding mathematical model and new calculation method development based on extension theory and extension mathematics[10-16].

Knowledge extension reuse technology is developed under this background[17-24] knowledge extension reuse in large-scale complex mechanism product design based on extension theory are analyzed and discussed here, and the knowledge extension reuse model for complex product design is given.

## 2 Extension reuse set of design scheme based on basic-element

### 2.1 BASIC-ELEMENT MODELING OF DESIGN KNOWLEDGE

Multi-types of domain design knowledge exist in scheme design process of large-scale complex product, the extraction, organization and modeling of all design knowledge assure the smooth implementation of design and reuse. Extenics uses basic-element theory and extension set theory to describe various design knowledge, the multi-dimensional basic-element model with the uniform quality and quantity will be established, which is particularly suitable for the research on storage, representtation and treatment of deep knowledge. The correspondding knowledge units are established according to different manifestations of design knowledge in complex product scheme design, the design knowledge are represented as three elements object $\Gamma$, feature $c$ and value $v$, which all composed into a orderly triple combination $\boldsymbol{J}=(\Gamma,c,v)$, called basic element of design object, basic-element for short. If an object has multiple characters, $n$ dimensional array are constituted by object $\Gamma$, $n$ characters such as $c_1,c_2,\cdots,c_n$ and correspondding value $v_1,v_2,\cdots,v_n$, as in Equation (1):

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$$\boldsymbol{J}=(\Gamma,c,v)=\begin{bmatrix}\Gamma & c_1 & v_1\\ & c_2 & v_2\\ & \vdots & \vdots\\ & c_n & v_n\end{bmatrix}, \tag{1}$$

It is regarded as basic element to describe the objects $\Gamma$, who called $n$ dimensional basic-element.

According to the design knowledge form in large-scale complex product, the knowledge units namely design objects can be divided into three types including matter-element type, affair-element type and relation-element type. Most matter-element type of design objects are static knowledge in product scheme design, which include structural knowledge, principle knowledge, cases, formulas, design constraints, descriptive knowledge, etc. the affair-element type of design objects are the design behaviors in product scheme design, which shown as design process knowledge and problems solving, judgment knowledge, etc. Relation-element type of design objects represent the effect and dependence among different design objects in product scheme design, which generally has shown as configuration relation, comparison relation, assembly relation, implication relation, etc. The various basic-element modeling provide an effective way for knowledge representation in product scheme design oriented to knowledge extension reuse.

### 2.2 THE ESTABLISHMENT OF DESIGN SCHEME EXTENSION REUSE SET

The establishment of basic-element models of design knowledge constructs basic knowledge units for the complex product scheme design. The corresponding basic-element set $\boldsymbol{S}_{J0}$ is formed based on this theory. The design knowledge of basic-element set $\boldsymbol{S}_{J0}$ can not completely meet the design requirements because of the change of design requirements. Therefore, scheme design needs to use the divergent, expansive, correlative, implicative and the relative extension transformation method to transform the basic-element in set $\boldsymbol{S}_{J0}$, divergent extension set, expansive extension set, correlative extension set and implicative extension set of basic-element and the relative extension transformation basic-element set with more abundant design knowledge are generated, which Collectively referred to as basic-element extension reuse set. Because product scheme design has specific design direction and design field, it need to meet the design requirements, so the basic-element extension reuse set of product scheme design is a basic-element set with specific design constraint called constrained basic-element extension reuse set. The constrained basic-element extension reuse set $\boldsymbol{S}_{J(T)}(L)$ defined as Equation (2):

$$\begin{aligned}S_{J(T)}(L)=\Big\{&\big(J,Y,Y^{'}\big)\,|\,J\in T_{W_J}W_J,\\ &Y=K\big(J;L\big)=k_{(L)}\big(x\big)\in\big(-\infty,+\infty\big),\\ &Y^{'}=T_K K\big(T_J J;T_L L\big)=T_k k_{(L^{'})}\big(x^{'}\big)\in\big(-\infty,+\infty\big),\\ &x^{'}=c_0\big(T_J J\big)\Big\}\end{aligned} \tag{2}$$

Here, $\boldsymbol{W}_J=\{\boldsymbol{J}\,|\,\boldsymbol{J}=(\Gamma,c,v)\}$ is a given basic-element set; $c_0$ is an evaluation characteristic of $\boldsymbol{J}$, and its value $c_0(J)=x$; $T=(T_W,T_K,T_J,T_L)$ is the transformation of design universe, dependent function, basic-element characteristics and constraints. $Y=k_{(L)}(x)$ is the dependent function of evaluating characteristic under the constraints condition $L$; $Y^{'}=T_K k_{(L^{'})}(x^{'})$ is the extension function of evaluating characteristic under the constraints condition $L^{'}$, when $\boldsymbol{J}\in T_{W_J}\boldsymbol{W}_J-\boldsymbol{W}_J$ is satisfied, $Y=k_{(L)}(x)<0$.

When design constraints and design requirements conflict with scheme design, the design requirements can be reached generally by decreasing constraints or adjusting the dependent function of evaluating characteristic, that is, the design requirements can be meet under the action implemented by extension transformation $T$. Thus, positive extension domain $\boldsymbol{S}^{+}_{J(T)}(L)$ of basic-element extension reuse set $\boldsymbol{S}_{J(T)}(L)$ is given as Equation (3):

$$\begin{aligned}\boldsymbol{S}^{+}_{J(T)}(L)=\Big\{&\big(\boldsymbol{J},Y,Y^{'}\big)\,|\,\boldsymbol{J}\in T_{W_J}\boldsymbol{W}_J,\\ &Y=K\big(\boldsymbol{J};L\big)\le 0,Y^{'}=T_K K\big(T_J\boldsymbol{J};T_L L\big)\ge 0,\Big\}\end{aligned}, \tag{3}$$

Similarly, positive stability domain $\tilde{\boldsymbol{S}}^{+}_{J(T)}(L)$ of basic-element extension reuse set $\boldsymbol{S}_{J(T)}(L)$ is given as Equation (4):

$$\begin{aligned}\tilde{\boldsymbol{S}}^{+}_{J(T)}(L)=\Big\{&\big(\boldsymbol{J},Y,Y^{'}\big)\,|\,\boldsymbol{J}\in T_{W_J}\boldsymbol{W}_J,\\ &Y=K\big(\boldsymbol{J};L\big)\ge 0,Y^{'}=T_K K\big(T_J\boldsymbol{J};T_L L\big)\ge 0,\Big\}\end{aligned} \tag{4}$$

## 3 Knowledge Extension Reuse of Scheme Design Based on Basic-element Extension Set

### 3.1 KNOWLEDGE BASE BUILDING BASED ON BASIC-ELEMENT MODEL

Knowledge acquisition of large-scale complex product scheme design mainly extract design knowledge which is used to solve the scheme design problems from some knowledge sources, and which is transformed into knowledge representation model stored in knowledge base for Identification. Knowledge sources mainly include expert design experience, design rules and criteria, design data and handbooks, technical literature, database and design cases, etc. In essence, the basic-element model of various design information and corresponding basic-element extension reuse set in product scheme design process is used to support the complex mechanism scheme design facing knowledge reuse formally and modeling. Therefore, the knowledge base, rule base and case base, etc corresponding with basic-element and extension set need to be constructed, which can support the product scheme design based on knowledge reuse effectively. Figure1 shows the construction framework of knowledge base based on basic-element model and basic-element extension set.

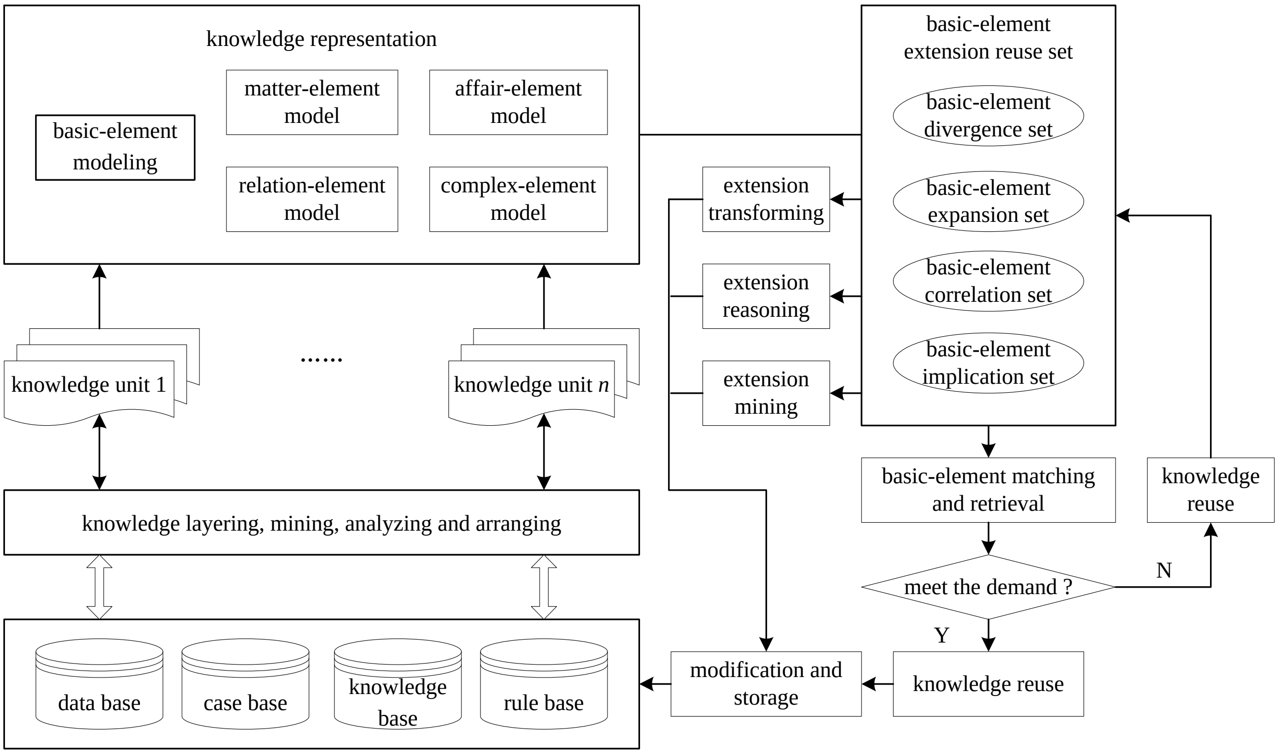


FIGURE 1. The knowledge base construction based on basic-element model and extension set

## 3.2 KNOWLEDGE EXTENSION REUSE MODEL BUILDING AND ALGORITHM IMPLEMENTATION

The building of design knowledge basic-element model and knowledge base provides support for the smooth implementation of knowledge reuse, the matching and searching problems of basic-element must be solved for reusing the design knowledge effectively. In practical applications, the design have both quantitative requirements and qualitative requirements, the former has fuzzy and usually given design requirements in the form of interval. So, the distance method based on extension theory to retrieve and match the basic-element are shown here.

If the basic-element is represented as:

$\boldsymbol{J}^0=\left(\Gamma^0,C^0,V^0\right)$,

and the basic-element of the ith design object which has common basic-element characters is represented as $\boldsymbol{J}(i)=\left(\Gamma(i),C(i),V(i)\right),1\le i\le m$. If the optimization values $v_j^0$ of the jth common basic-element design requirements character $c_j$ is the midpoint of the design requirements interval, that is $v_j^0=\left(v_j^{0L}+v_j^{0R}\right)/2$, then the distance $\rho_i\left(c_j\right)$ about the common character $c_j$ between the basic-element $\boldsymbol{J}(i)$ of design object and the basic-element $\boldsymbol{J}^0$ of design requirements is as Equation (5):

$$\rho_i\left(c_j\right)=\left|v_i\left(j\right)-\frac{v_j^{0L}+v_j^{0R}}{2}\right|-\frac{1}{2}\left(v_j^{0R}-v_j^{0R}\right), \tag{5}$$

here, $v_j^{0L}$ 、 $v_j^{0R}$ is the limit values of design requirements character $c_j$, $v_j^{0L}\le v_j^{0R}$.

If the optimization values $v_j^0$ of the jth common basic-element design requirements character $c_j$ is $v_j^o\in\left[v_j^{0L},\left(v_j^{0L}+v_j^{0R}\right)/2\right]$, then the distance $\rho_i\left(c_j\right)$ is as Equation (6):

$$\rho_i\left(c_j\right)=\begin{cases} v_j^{0L}-v_i\left(j\right), & v_i\left(j\right)<v_j^{0L} \\ \dfrac{v_j^{0R}-v_j^0}{v_j^{0L}-v_j^0}\left(v_i\left(j\right)-v_j^{0L}\right), & v_j^{0L}\le v_i\left(j\right)\le v_j^0 \\ v_i\left(j\right)-v_j^{0R}, & v_i\left(j\right)>v_j^0 \end{cases} \tag{6}$$

Different character has different dimension, the distance needs to be standardized for matching and retrieval easily. The standardized distance is as Equation (7):

$$\begin{cases} \overline{D_i}(c_j) = -\rho_i(c_j) / \max\limits_{1 \le i \le n} \rho_i(c_j), & \rho_i(c_j) > 0 \\ \overline{D_i}(c_j) = 0, & \rho_i(c_j) = 0 \\ \overline{D_i(c_j)} = -\rho_i(c_j) / \max\limits_{1 \le i \le n} |\rho_i(c_j)|, & \rho_i(c_j) < 0 \end{cases} \quad (7)$$

Then, the basic-element extension reuse degree $\Omega_S$ is as Equation (8):

$$\Omega_S = \sum_{j=1}^{n} (w_j * \overline{D_i(c_j)}), \quad (8)$$

Here, $w_j$ is the weight of each common character, $w_1 + w_2 + \cdots + w_n = 1$.

The searching and matching are realized according to basic-element extension reuse degree, the basic-element extension reuse is completed. The implement steps are described as follows:

Step1: The basic-element model $J$ of design object are established according to the types of domain design knowledge, the basic-element extension reuse set $S_{J(T)}(L)$ are generated and the corresponding knowledge base are set;

Step2: The requirement character and its mapping are extracted according to the design requirements, the basic-element model $J^0$ of design requirements are set;

Step3: The knowledge base are searched for the basic-element who match to the requirement basic-element model, the distance $\rho_i(c_j)$ about the common character $c_j$ between the basic-element $J(i)$ of design object and the basic-element $J^0$ of design requirements are calculated by formula 5;

Step4: The extension distance with different dimension are standardized based on formula (7), the extension reuse degree $\Omega_S$ of design object basic-element $J(i)$ are obtained based on formula (8);

Step5: The best reuse design object are obtained by choosing $\Omega_S = \max(\Omega_S(1), \Omega_S(2), ..., \Omega_S(m))$, which is reused in new scheme design, then overall scheme design parameters which meet user demands and technical requirements is obtained;

Step6: If the new design scheme does not meet the design requirements, which need be redesigned; if multi design schemes exist, the best design scheme should be selected;

Step7: The design information in new scheme design is extracted, corresponding knowledge units and basic-element model are established, which are stored in knowledge base, rule base or case base, the reuse end.

## 4 Application Examples

Large-scale Hydropower Station Selection is regarded as design illustration. Because of the complexity of fluid motion and the imperfection of design theory, the production mode of large-scale hydraulic turbine manufacturing is single piece, small batch and large complete set, therefore, hydraulic turbine scheme design process and various type of design knowledge are summarized, it has practicality for applying past design knowledge of hydraulic turbines to new scheme design by a series of process such as acquisition, representation, storage and reuse of knowledge.

The scheme design of large-scale hydraulic turbine has many design directions and design fields such as mixed flow, axial flow, diagonal flow, tubular and Pelton, which satisfy the design constraints requirements in different design field such as maximum head, head range, output. The hydropower station uses mixed flow turbine for scheme design selection, and the corresponding characters and values of design requirement show in Table 1.

TABLE 1. Scheme design selection of hydraulic turbine

| maximum head(m) | minimum head(m) | rated head(m) | rated output(MW) | efficiency range |
|---|---|---|---|---|
| 121.2~122.7 | 80.5~80.9 | 102.8~103.2 | 300 | ≥92% |

Basic-element is firstly modeled according to the design requirements. The basic-element model $J^0$ is obtained:

$$J^0 = \begin{bmatrix} \text{design requirements} & \text{maximum head(m)} & 121.2 \sim 122.7 \\ & \text{minimum head(m)} & 80.5 \sim 80.9 \\ & \text{rated head(m)} & 102.8 \sim 103.2 \\ & \text{rated output(MW)} & \ge 300 \\ & \text{efficiency} & \ge 92\% \end{bmatrix};$$

Then, according to the maximum head and head range, the model runner is searched from the knowledge base which is corresponding to basic-element extension reuse set of runner.

$$J(1) = \begin{bmatrix} \text{runner A384} & \text{maximum head(m)} & 125.0 \\ & \text{unit speed(r/min)} & 77.7 \\ & \text{unit discharge(m}^3\text{/s)} & 1017.0 \\ & \text{efficiency} & 93.1\% \end{bmatrix};$$

$$J(2) = \begin{bmatrix} \text{runner A464} & \text{maximum head(m)} & 125.0 \\ & \text{unit speed(r/min)} & 80.0 \\ & \text{unit discharge(m}^3\text{/s)} & 1026.0 \\ & \text{efficiency} & 92.5\% \end{bmatrix};$$

$$J(3) = \begin{bmatrix} \text{runner A466} & \text{maximum head(m)} & 125.0 \\ & \text{unit speed(r/min)} & 73.0 \\ & \text{unit discharge(m}^3\text{/s)} & 1068.0 \\ & \text{efficiency} & 92.4\% \end{bmatrix};$$

$$J(4) = \begin{bmatrix} \text{runner A522} & \text{maximum head(m)} & 130.0 \\ & \text{unit speed(r/min)} & 70.0 \\ & \text{unit discharge(m}^3\text{/s)} & 1012.0 \\ & \text{efficiency} & 92.4\% \end{bmatrix};$$

The maximum head, the unit speed and the unit discharge are taken as common characters of extension reuse degree calculation of type selection design, and the corresponding weight is $W=(0.5,0.25,0.25)$, the basic-element extension reuse degree sequence is:

$\Omega_S=(0.959,0.715,0.617,0.466)$,

which obtained from the basic-element retrieval and matching algorithm discussed in 2.2. According to the principle of closeness choosing, runner A384 is the best reuse object, thus the follow-up scheme design of hydraulic turbine can be carried out, including type selection design of cubical tunnel, spiral case, guide vane, etc and structural scheme design. Meanwhile, runner A464 and A466 all meet a certain design threshold demand, and their values of characters can be diverged by hydraulic turbine design knowledge, the extension adaptive design of type selection is realized and abundant design schemes can be obtained, then various design requirements can be meet.

## 5 Conclusions

The knowledge extension reuse technology in product scheme design process is discussed here, several aspects of domain knowledge basic-element modeling, design knowledge extension reuse set establishing, and basic-element knowledge base building and design knowledge extension reuse model and algorithm design in complex mechanism scheme design process are analyzed. It is verified by a scheme design application illustration of hydraulic turbine selection. The application of design knowledge extension reuse model provides a new way for product design reuse and complex mechanism scheme design application.

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