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DESIGN KNOWLEDGE REPRESENTATION AS AN INTEGRATION OF FUNCTIONAL KNOWLEDGE MODELLING AND DESIGN STRUCTURE MATRIX

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Abstract

Design knowledge representation has been regarded as a key aspect in design processes, especially at the early stage of conceptual design as it establishes the basis for the subsequent design activities. This paper presents a systematic knowledge representation model called Requirement-Function-Principle solution-Structure (RFPS), in which functional knowledge model (FKM) is proposed to represent the mapping relationships between the function layer and structure layer and to strengthen the design knowledge reuse in conceptual design. By investigating the mapping process, a transformation matrix (TM) is developed to reveal the mapping relations between the function representations and structure parameters and to identify whether the decomposition of the function layer reaches the lowest level. Then design structure matrix (DSM) is introduced to combine with RFPS to enhance the representation of the internal interactions of the function layer and structure component. A matrix transformation algorithm is put forward to facilitate the conversion procedure between TM and DSM. Finally, a case study is presented to demonstrate the proposed approach.

Keywords: Conceptual design, Functional modelling, Design cognition, Knowledge representation, Design structure matrix

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1 INTRODUCTION

Knowledge representation and reasoning mainly devotes to representing information in such a way that a computer can adopt in problem-solving. It has been widely recognized as one of the most important topics in conceptual design as it provides the basis for the entire design processes. As an effective design knowledge modelling tool, functional modelling has attracted more attentions and many function-based design models have been developed, such as Axiomatic Design (AD) (Suh, 2001), Function-Behaviour-Structure (FBS) (Gero, 1990), Requirement-Function-Behaviour-Structure (RFBS) (Christophe, Bernard and Coatanéa, 2010), Funtion-Cell-Behaviour-Structure (FCBS) (Gu et al., 2012) and functional case modelling (Gu, Hu and Peng, 2012). Most of the design models are established on studying the mapping process between different design domains. Among them, many attentions have been paid to the mapping operation between the function layer and structure layer. However, it fails to capture the internal interactions within the single domain, such as the interactions among structure parameters in the physical domain.

Meanwhile, as a prevalent structured modelling approach, design structure matrix (DSM) is skilled in the representation of system decomposition and integration as well as design process analysis (Steward, 1981). It can effectively reveal the interactions between product elements for the existing products. But at the conceptual design or for a new product, it is difficult to build DSM due to the lack of detailed information and relative experience. In other words, DSM is incapable in new product development and fails to support the innovative design (Tang, Zhang and Dai, 2009). Therefore, to develop a design knowledge representation model to support the mapping process between different domains and indicate the internal relations within the domain becomes an urgent task.

The main purpose of this paper is to propose a comprehensive design knowledge representation model to facilitate the process of conceptual design which is known as Requirement-Function-Principle solution-Structure (RFPS). Functional knowledge model (FKM) is presented to describe the mapping relationships between the function and structure layer and enhance the design knowledge reuse. A transformation matrix (TM) is built to describe the mapping relations between the two layers and used to identify whether the function decomposition is accomplished. Then DSM is introduced to combine with RFPS to strengthen the representation of the internal interactions of the structure component. A transformation algorithm is developed to facilitate the transition process between TM and DSM.

The rest of this paper is organized as follows. Section 2 presents the RFPS based functional knowledge modelling method. Section 3 outlines the basic concept of DSM. The framework and implementation of the integrated RFPS and DSM is depicted in Section 4. Section 5 proposes a case study to demonstrate the proposed method. The conclusion is drawn in Section 6.

2 REQUIREMENT-FUNCTION-PRINCIPLE SOLUTION-STRUCTURE BASED FUNCTIONAL KNOWLEDGE MODELLING METHOD

To develop a design concept to meet the customer requirement is the basic purpose of the conceptual design. However, most of the traditional knowledge representation models have not taken the requirement analysis into consideration. Compared with the traditional design models, this paper presents a RFPS model which is depicted in Figure 1. As illustrated in RFPS, the design process starts with the requirement analysis which involves transformation of design requirement into the representation of expected functions and design constraints (Ma et al., 2013). Then retrieve the principle solution library for corresponding principle solution to specific expected function. The retrieve process can be conducted by similarity measurement and the mapping process from the requirement to principle solution is accomplished. Next, decompose the principle solution function into sub functions and retrieve the FKM library to find the most similar FKM for the corresponding sub function. Finally, revise or reuse the retrieved FKM as the final design concept.

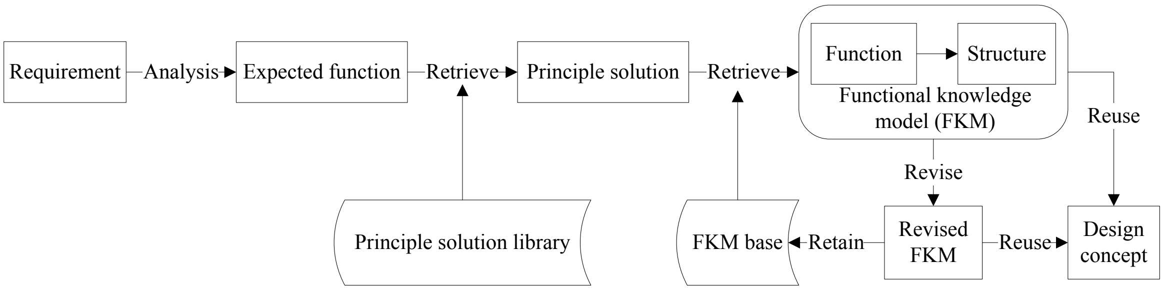

Figure 1. Design process with RFPS

To establish the mapping relations and capture internal interactions of the function and structure layer, this paper introduces the knowledge model of FKM which is illustrated in Figure 2. Generally, FKM is an integration of the function layer knowledge and structure layer knowledge which is described as:

$$FKM_i = F_i \oplus S_i \tag{1}$$

where $\oplus$ is an integration symbol, F_i is the function layer knowledge and S_i is the structure layer knowledge.

Furthermore, the function block (F_i) can be denoted by input/output flows and transitive verb.

$$F_i = I_i \oplus Tv_i \oplus O_i \tag{2}$$

where I_i and O_i are the input and output flow, respectively; Tv_i is the transitive verb.

In the function layer, function block is adopted to represent the function knowledge which is composed of input/output flow and the transitive verb. Function decomposition tree is built to illustrate the decomposition process of the function. In the structure layer, structure integrates the structural information, such as material, geometry and topology. Functional ontology is developed to depict the relations of the corresponding functions as well as the mapping between function layer and structure layer. The integration of the function layer, structure layer and the mapping relations between two layers constitute the model of FKM. Then the FKM is stored in the FKM library for design reuse. Between the two layers, a transformation process is introduced to reveal the mapping relationships.

$$\{F\} = [A]\{S\} \tag{3}$$

where $[A]$ is known as 'transformation matrix' which is used to denote the relationships between the function representations and structure components. The transformation matrix is also used to identify whether or not the function decomposition meet the independence requirement of the structure component. If the transformation matrix is uncoupled (diagonal) or decoupled (triangular), the function decomposition reaches the end. Otherwise, if the transformation matrix is coupled, it can be further decomposed (Li, Hu and Peng, 2010; Hu, 2011).

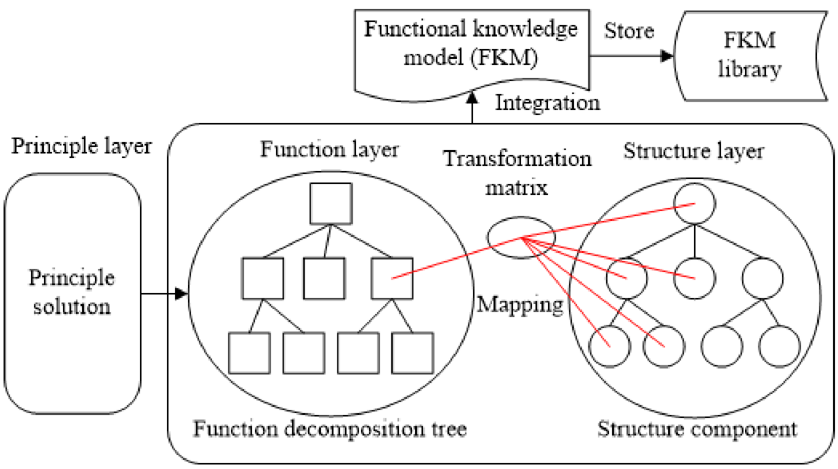

Figure 2. Framework of FKM

3 DESIGN STRUCTURE MATRIX

The DSM was first proposed by Steward for complex system and process representation and analysis (Steward, 1981). It has been widely used as a powerful tool in system decomposition and integration, product development and management as well as information flow analysis. A DSM provides a visual and compact representation for the task interaction analysis of a complex system. System components are usually located at the left of the column and the above of the row. The elements represent the interactions between two system components, such as spatial, energy, information and material. Generally, the elements are marked with the shadow along the diagonal while the off-diagonal ones indicate the relationships of one element to another. Those interactions are quantified to depict strengths of the relationships between components. The marks above the diagonal indicate the feedback of the information flow between corresponding elements while the below ones represent the feedforward. As illustrated in Figure 3, the mark in row B and column A means A is an input to B while the mark in row A and column D indicates D provides an input to A.

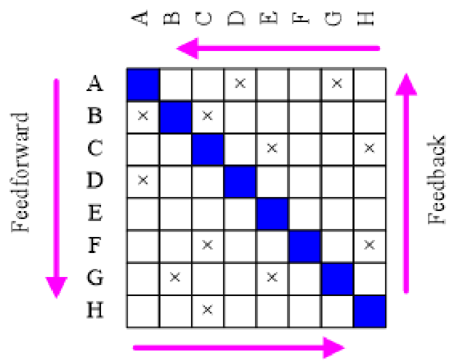

Figure 3. The general DSM form

As a popular tool in project process management and system interaction analysis, a lot of researches have been conducted among the development of DSM (Browning, 2011; Eppinger and Browning, 2012). In general, there are two main classes of DSM: static DSM and time-based DSM. The former one indicates system elements existing simultaneously while the later one means the ordering of rows and columns complies with a strict time sequence: upstream activities proceed prior to downstream activities. The static DSM can be further divided into component-based DSM and team-based DSM while the time-based DSM contains activity-based DSM and parameter-based DSM. Many algorithms are developed for the elements reordering in matrix analysis with respect to various criteria. In the static DSM, clustering algorithm is a useful approach in integration analysis. It seeks an optimized DSM configuration and reorders the rows and columns of the matrix by clustering highly related elements together. By clustering, engineers can examine the structure of the system and identify the interfaces of the clusters more easily. Besides clustering algorithm, partitioning and tearing are two popular methods in the analysis of time-based DSM. Partitioning focuses on reordering the rows and columns simultaneously to produce a lower triangular matrix to minimize possible feedback loops. Tearing is implemented by identifying possible feedback marks that if removed from the matrix, it will obtain a DSM with low triangle after repartitioning. The removed marks are known as 'tears'. The identification of the tears is established on the assumptions that the marks have the least impact to the entire process. By removing the tears, the purpose of eliminating the information feedback to reduce design couplings or iterations can be obtained.

At present, numeric values are generally used to substitute the binary marks (also known as Boolean DSM) to represent the strengths of the interactions in DSM. The quantification of the binary marks mainly rely on experts' subjective judgments with respect to the criteria of spatial, energy, information and material. However, it is difficult or even impossible when faced with a new product due to the poor experience or knowledge about the interactions of the product elements. This situation is also common in the early phase of product design, such as the stage of conceptual design. In such circumstance, there lacks detailed information for experts to give their judgments to construct a DSM for design analysis. In addition, DSM mainly provides the insights into the interaction among elements in a system, but fails to capture the reasons for the interactions (Dong and Whitney, 2001).

4 INTEGRATION OF RFPS AND DSM

4.1 Integration framework of RFPS and DSM

While RFPS based functional knowledge modelling plays an important role in design knowledge representation and reuse in conceptual design, especially in the representation and analysis of the mapping relationships between function layer and structure layer. DSM is an effective approach to record and analysis the interactions between the structure components within the structure layer. Thus those two methods can be combined together to further enhance the knowledge representation in design process. For the purpose of further promoting the process of design knowledge modelling and representation, this paper presents a systematic knowledge representation framework by combining with RFPS based functional knowledge modelling and DSM. FKM is developed and used in the functional knowledge modelling and reuse at the design stage. A transformation matrix is obtained in the investigation of mapping process between function layer and structure layer to reveal the mapping relationships between the two layers. After the construction of the mapping between the two layers, a transformation algorithm is put forward to facilitate the conversion process between RFPS and DSM. A DSM is generated after the transition procedure. By combining with RFPS and DSM, the shortcomings of both techniques can be well addressed and the advantages of both technologies can be strengthened. The problem of representation of the mapping relations between the function layer and structure layer as well as interaction analysis within the structure layer can be well manipulated.

4.2. Transformation algorithm between TM and DSM

To promote the transition from RFPS modelling to DSM construction, a matrix transformation algorithm is presented to enhance the conversion between TM and DSM, which is illustrated in Figure 4. The transition procedure is described as follows:

Step 1: Construct a transformation matrix (TM).

Step 2: Assign the diagonal element in the matrix as a dominant element. The diagonal elements in a TM indicate that the S_i have major contributions to the corresponding F_i (Dong and Whitney, 2001). Thus, the non-diagonal elements are served as output variable set, which are represented as 'X0'.

Step 3: Use the dominant elements to represent the S_i in the output variable set.

Step 4: Arrange the matrix by exchanging rows to make all the output variables on the diagonal. Then a transition matrix is obtained.

Step 5: Substitute 'X0' with 'X'. The final DSM is generated and the transformation between TM and DSM is accomplished.

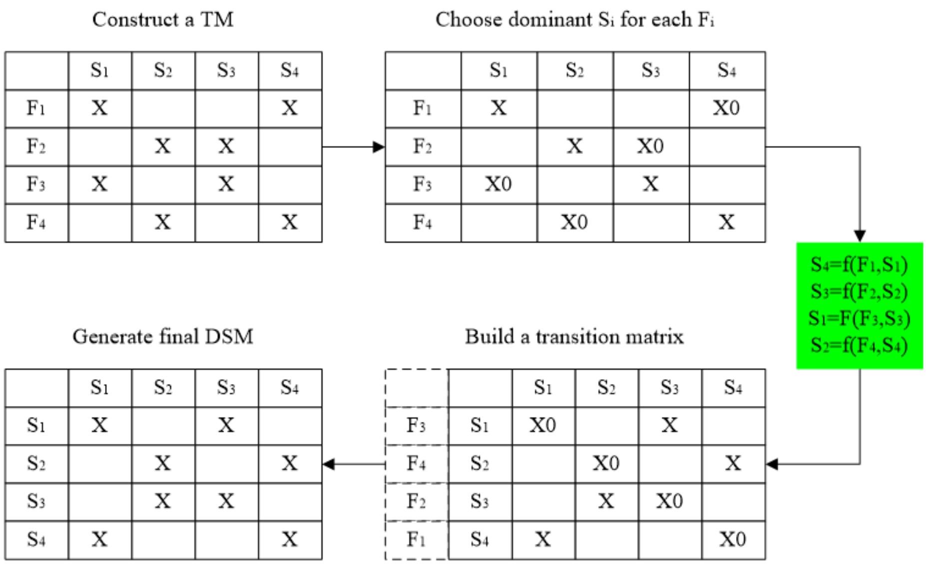

Figure 4. Transformation of TM to DSM

5 CASE STUDY

In this section, an implementation is proposed to evaluate the proposed method. A support mechanism is widely used in many industry areas, such as civil engineering, automotive, construction equipment and mining machinery. Correspondingly, the expected function of the requirement 'support mechanism' is 'support'. By retrieving the principle solution library, there are many principle solutions which can meet the functional requirement, such as hydraulic cylinder, pneumatic cylinder, hydraulic jack and spring support mechanism. Due to the design constraints and its unique advantage of smooth moving, reliable working and simple structure, a hydraulic cylinder is selected as a principle solution to fulfill the expected function. A general hydraulic cylinder is illustrated in Figure 5.

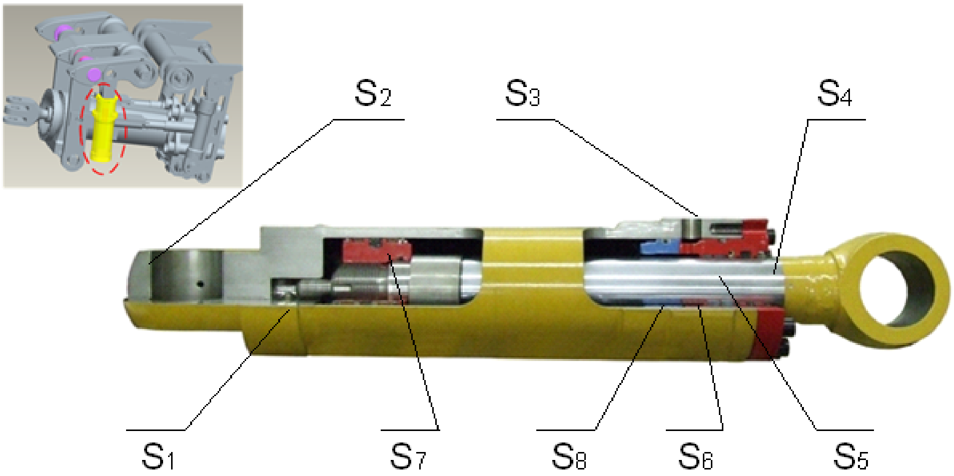

Figure 5. Illustration of a hydraulic cylinder

Generally, in a hydraulic system, the hydraulic pump acts as a 'generator' while a hydraulic cylinder plays the part of an 'actuator'. The hydraulic pump provides a fixed or regulated hydraulic flow to drive the piston. At the same time, the piston moves and pushes the oil back to the reservoir under the pressure difference between the two sides of the chamber. Therefore, the main function of a hydraulic cylinder is converting pressure into linear force. The primary function is described as:

$F = convert(pressure, force)$

By investigating the operational mechanism of the hydraulic cylinder, the function knowledge is extracted. Typically, a hydraulic cylinder is composed of piston, piston rod, piston head, rod gland, cylinder barrel, cylinder head, cylinder bottom and seals, which are described as:

$S_1 = cylinder\ barrel$

$S_2 = cylinder\ bottom$

$S_3 = cylinder\ head$

$S_4 = piston\ head$

$S_5 = piston\ rod$

$S_6 = rod\ gland$

$S_7 = piston$

$S_8 = seals$

In a hydraulic cylinder, hydraulic oil is contained in a chamber which is surrounded by cylinder barrel, cylinder head and cylinder bottom. Meanwhile, the piston and the piston rod constitute an integral part to convert the pressure into force. The piston rod is supported and guided by the rod gland as it moves. Seals are adopted to prevent potential leakage. Therefore, the function layer can be depicted as:

$F_1 = contain(hydraulic\ cylinder, oil)$
$F_2 = convert(pressure, force)$
$F_3 = support(rod\ gland, piston\ rod)$
$F_4 = guide(rod\ gland, piston\ rod)$
$F_5 = prevent(seals, leakage)$

By studying the function domain and structure components, the mapping relations between the two layers is established as:

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \end{bmatrix} = \begin{bmatrix} x & x & x & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & x & x & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & x & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & x & 0 \\ x & 0 & 0 & 0 & x & 0 & 0 & x \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ S_7 \\ S_8 \end{bmatrix}$$

As the transformation matrix is coupled, the function can be further decomposed into sub functions. Furthermore, to contain hydraulic oil, the cylinder bottom and cylinder head is assembled with seals to prevent leakage. The piston head transports the pressure and the piston rod transports the linear force. Thus, F_1 and F_2 are further decomposed as:

$F_{11} = contain(cylinder, oil)$
$F_{12} = prevent(cylinder\ bottom, oil\ leakage)$
$F_{13} = prevent(cylinder\ head, oil\ leakage)$
$F_{21} = transport(piston\ head, pressure)$
$F_{22} = transport(piston\ rod, force)$

Then, the mapping process is developed as:

$$\begin{bmatrix} F_{11} \\ F_{12} \\ F_{13} \\ F_{21} \\ F_{22} \\ F_3 \\ F_4 \\ F_5 \end{bmatrix} = \begin{bmatrix} x & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & x & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & x & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & x & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & x & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & x & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & x & 0 \\ x & 0 & 0 & 0 & x & 0 & 0 & x \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ S_7 \\ S_8 \end{bmatrix}$$

The transformation matrix is described as:

$$A = \begin{bmatrix} x & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & x & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & x & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & x & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & x & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & x & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & x & 0 \\ x & 0 & 0 & 0 & x & 0 & 0 & x \end{bmatrix}$$

On the basis of the transformation algorithm stated in Section 4.2, the DSM of the hydraulic cylinder is obtained which is depicted in Figure 6.

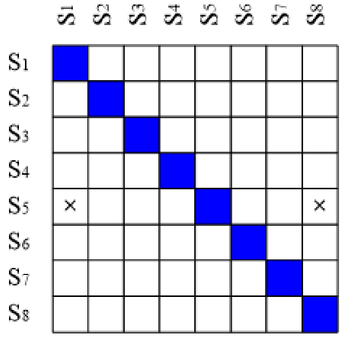

Figure 6. The generated DSM for the hydraulic cylinder

Therefore, the functional knowledge representation and the structure interactions are well captured and manipulated by combining with RFPS model and DSM construction. Then the case is stored in a case library as a functional case cell for functional case design (Gu, Hu and Peng, 2012), modular design or case-based design.

6 CONCLUSION

Due to the important role of knowledge representation in conceptual design, this paper proposes an integrated knowledge representation model which combines with RFPS and DSM to systematically represent the processes of functional knowledge modelling and structure component interaction. FKM is presented to capture the mapping relations between function domain and structure layer and strengthen the knowledge reuse. Function decomposition tree is adopted in the decomposition of function layer. A transformation matrix is developed during the mapping process between function domain and structure layer. Based on the FKM, this paper presents a RFPS based conceptual design model to conduct the design knowledge modelling in conceptual design. Then a conversion algorithm is proposed to facilitate the transition between TM and DSM. DSM is introduced to reveal the internal interactions among structure components in structure layer. By integrating with RFPS and DSM, the problem of design knowledge representation can be properly addressed. Finally, a case study is put forward to demonstrate the effectiveness of the proposed method. The implementation shows that the hybrid model can not only illustrate the mapping relations, but also enhance the internal knowledge representation of both layers.

In the future, more studies are required to validate the performance of the modelling method. The proposed design knowledge representation model will be generalized and used in the subsequent design phases, such as functional case design, case-based reasoning, modular design and product flexibility design. More attentions will be paid on the analysis and representation of complex product development.

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