Proceedings of ICAD2009
The Fifth International Conference on Axiomatic Design
Campus de Caparica – March 25-27, 2009
ICAD-2009-10

DECOMPOSITION PROCESS OF ENGINEERING SYSTEMS USING AXIOMATIC DESIGN AND DESIGN STRUCTURE MATRIX

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ABSTRACT

One of the most active areas of engineering design today is a modular design method to design and to produce a large variety of product in a limited time and a lower cost. Decomposition of system into modules is the most important part of the modular design method. Design Structure Matrix (DSM) has been proposed for efficient modularization. However, DSM does not indicate the design flow. It is well known that a good design flow can be defined by axiomatic design. In this paper, a rational method is presented to define modules considering relationships between functional requirements and design parameters and interactions of design parameters within. The Independence Axiom of Axiomatic design and Design Structure Matrix (DSM) are utilized for efficient modularization of a design system and the design flow without feedbacks. The method is applied to the ceiling type air conditioner and the results are analyzed.

Keywords: Design Structure Matrix (DSM), Decomposition, Modular design.

1 INTRODUCTION

The increasing heterogeneity in contemporary marketplaces, wider income distribution, and the slower growth within the market, are driving the need for increased product variety [Martin and Ishii, 2002]. Developing robust product platform architectures with modular and standardized components could enhance the ability of companies to bring products to the market faster and gain an important competitive advantage [Pine, 1993]. The major benefits of a modular design include: efficient upgrades; reduced complexity; reduced costs; rapid product development and improved knowledge structuring [Muffato, 1999, O'Grady and Liang, 1998].

The first step is a rational module definition to utilize these advantages of the modular design. The Design Structure Matrix (DSM) approach is one of the well-known methods to define rational modules. The DSM is a popular representation and analysis tool for system modeling, especially for purposes of decomposition and integration. A DSM displays the relationships between components of a system in a compact, visual, and analytically advantageous format [Browning, 2002] and decomposes a system into sub-systems from the viewpoint of an inter-relationship between components of the system. The decomposed sub-system can be used as a module in the system design and manufacturing.

Although DSM can define the modules from a viewpoint of relationships between components, the DSM cannot consider the relationships between functions and the components of the systems. These relationships between functions and components are quite important information to design the system and/or the modules. How to design a system with the modules which are defined by the DSM approach is still an issue to be solved because of the absence of the relationship information. To overcome these difficulties, a new decomposition method is required to define rational modules to consider the relationships between functions of the system and the components.

Axiomatic design can be the solution to overcome the presented difficulties. There are some researches to link axiomatic design and DSM to define modules to consider the system design. Dong and Whitney [2001] claimed that if the axiomatic design matrix can be expressed analytically and one design parameter (DP) is dominant in satisfying a particular functional requirement (FR), then the triangulated design matrix is equivalent to the DSM of the design parameters. The analytical expression of the axiomatic design matrix, however, is very difficult and sometimes impossible when designing complex systems. Guenov and Barker [2005] proposed the COPE (decomposition-integration of COmplex Product Environments) model to define effective modules for a new product that has never been designed but the COPE model has the same difficulties of the Dong and Whitney's method because the authors adopt the same idea of the Dong and Whitney's method to link axiomatic design matrix and DSM.

In this paper, a new method is proposed to link the axiomatic design and DSM approach to define effective and rational modules from the viewpoint of a design and manufacturing. The proposed method uses DSM and axiomatic design simultaneously to define modules, and axiomatic design is solely used to design the system and/or defined modules. The modules which considered relationships between components, and relationships between functions of the system and components can be defined with the proposed method. A mount type HVAC system is used to verify the proposed method and the results are discussed.

2 DESIGN STRUCTURE MATRIX

The DSM is a popular representation and analysis tool for system modeling, especially for purposes of decomposition and integration. There are two main categories of DSMs: static and time-based. Static DSMs represent system elements existing simultaneously, such as components of a product architecture or groups in an organization. Static DSMs are usually analyzed with clustering algorithms [Pimmler and Eppinger, 1994]. In time-based DSMs, the ordering of the rows and columns indicates a flow through time: upstream activities in a process precede downstream activities, and terms like "feedforward" and "feedback" become meaningful when referring to interfaces [Eppinger *et al*, 1994]. Time-based DSMs are typically analyzed using sequencing algorithms [Steward, 1981, Browning, 2001]. There are four types of DSMs: component-based, team-based, activity-based and parameter-based and each of the four applications is applied to system decomposition and/or integration problem in the Table 1.

Among the four types of DSMs, component-based DSM is used for modeling system architectures based on components and/or subsystems and their relationships. The component-based DSM represents the system in terms of the relationships between its constituent components and the represented system is decomposed into several sub-systems to define modules of the system. In general, modules can be defined by the following three steps [Pimmler and Eppinger, 1994] and the process is shown in Figure 1:

1) **Decompose system into elements:** Describe the product concept in terms of functional and/or physical elements which achieve the product's functions.
2) **Document the interactions between elements:** Identify the interactions which may occur between the functional and physical elements.
3) **Cluster the elements into modules:** Cluster the elements into chunks based on criteria set by the overall product design strategy of the team. These chunks then define the product architecture and system team structure.

A component-based DSM documents interactions among elements in a system architecture. The number and definitions of the interaction types can be different by the given design problem, and Pimmler and Eppinger [1994] suggested four types as follows:

Spatial: A spatial-type interaction identifies needs for adjacency or orientation between two elements.

Energy: An energy-type interaction identifies needs for energy transfer between two elements.

Information: An information-type interaction identifies needs for information or signal exchange between two elements.

Material: A material-type interaction identifies needs for materials exchange between two elements.

The interactions should be quantified to describe strengths of relationships between elements. The quantification can be different by the design problems, and Pimmler and Eppinger [1994] suggested a five-point scale (-2, -1, 0, 1, 2) based on the relative need for each interaction type. After the interactions have been quantified, the next step is to cluster the elements into modules. There are several algorithms to cluster the elements including genetic algorithm (GA), fuzzy logic, distance penalty algorithm [Rissinen, 1978], and so forth. Figure 2 illustrates an example of the component-based DSM of a climate control system of an automobile researched by Pimmler and Eppinger [1994].

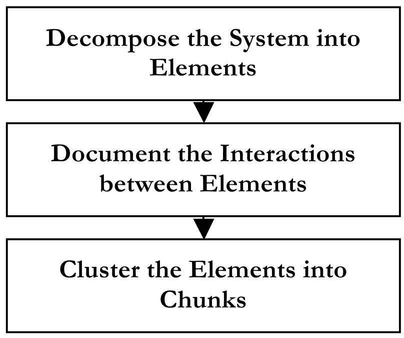


Figure 1. Decomposition process of component-based DSM

Table 1. Four types of DSMs

DSM Data Types	Representation	Application	Analysis Method
Component-based	Multi-component relationships	System architecting, engineering and design	Clustering
Team-based	Multi-team interface characteristics	Organizational design, interface management, team integration	Clustering
Activity-based	Activity input/output relationships	Project scheduling, activity sequencing, cycle time reduction	Sequencing & Partitioning
Parameter-based	Parameter decision points and necessary precedents	Low lever activity sequencing and process construction	Sequencing & Partitioning

Although DSM provides a powerful technique for the analysis and decomposition of the complex system, DSM presents some difficulties to reflect the relationships between the functions of the system and elements of the DSM. How to design the system with the clustered modules and/or elements, therefore, is still an issue to be solved. To overcome this difficulty, a new decomposition method which can consider the relationships between functions and elements is required.

3 DECOMPOSITION PROCESS OF ENGINEERING SYSTEMS

3.1 RELATIONSHIP BETWEEN AXIOMATIC DESIGN AND DSM

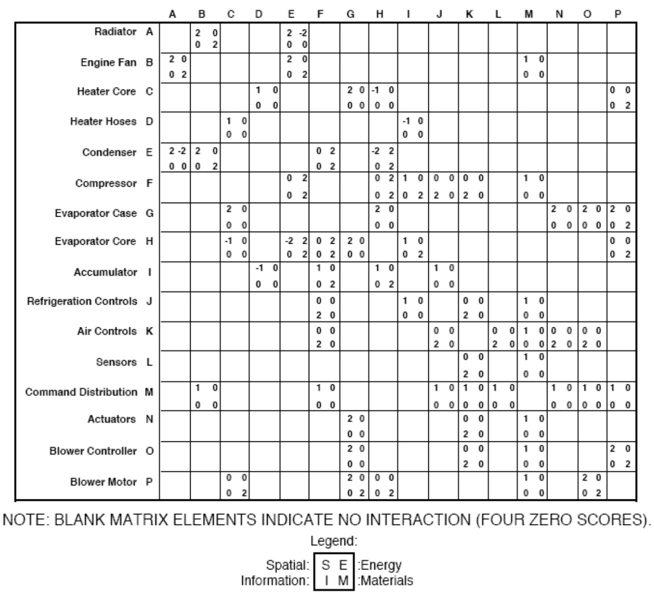
To analyze and decompose the system with DSM, three steps of operation are required as illustrated in Figure 1. The most important step among these three steps is the second step because the system is decomposed based on the quantified relationship information of this step. The quantification of the relationship can be obtained by various ways such as interviewing and surveying engineering team members, researching on the existing hardware and so forth. Relationship tables are used to summarize and quantify the relationships between elements and Figure 3 illustrates a relationship table example.

This quantification of relationship is based on the knowledge of the engineering members and/or experts who has well-structured knowledge about the system. The knowledge of the engineering members and/or experts includes information about the functions of the elements, interactions between elements, characteristics of the system, and so forth. The functional requirement [Suh, 1990, 2000] of the system, moreover, is also included in the knowledge about the system. Knowledge of functional requirements can be found in the relationship table in Figure 3. In the relationship table, basic functions of the element are explained first, and then the relationships between the elements is explained and quantified for four interaction types. The relationship table shows that functional requirements of the system are implicitly used in decomposition of the system using DSM.

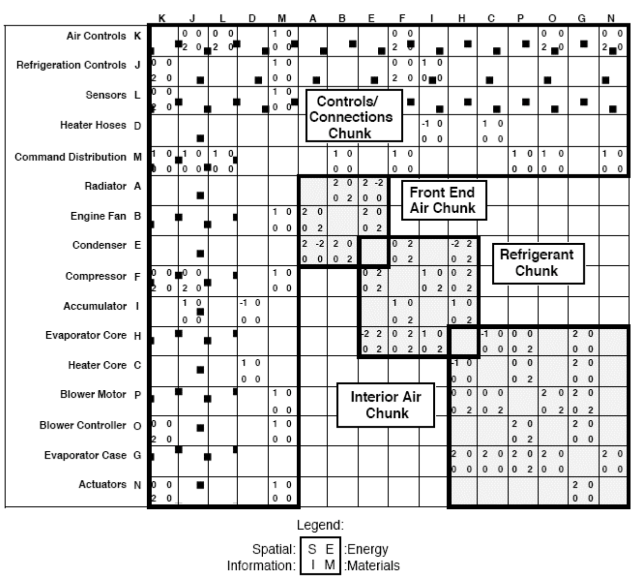
In this paper, a new decomposition method to link axiomatic design and DSM is proposed based on the functional requirements which are implicitly used to

Elements:	**Radiator and Engine Fan**		
Function: (Radiator)	The radiator dissipates excess engine heat, via forced convection, to the outside surroundings.		
Function: (Engine Fan)	The engine fan draws outside air into the engine compartment.		
Relationship:	The engine fan **provides airflow** across the radiator. They are **located in close proximity** for design efficiency and due to space management constraints.		
Score:	Spatial: +2 Information: 0	Energy: 0 Materials: +2	

Figure 3. Relationship table of climate control system of an automobile (adopted from Pimmler and Eppinger [1994])



(a) DSM of the climate control system example



(b) Clustered DSM of the climate control system example

Figure 2. DSM example for an air-climate control system of an automobile (adopted from Pimmler and Eppinger [1994])

decompose the system using DSM. Implicitly used functional requirements are expressed explicitly to link axiomatic design and DSM. After the explicit expression of functional requirements, design parameters corresponding to each functional requirement are selected from the existing sub-system, individual part, and/or parameters. The axiomatic design matrix, then, is constructed with the defined functional requirements and design parameters.

3.2 DECOMPOSITION PROCESS

The process of the proposed decomposition method is illustrated in Figure 4 and the processes are as follows:

Step 1. Decompose system into elements: the system is described with a set of sub-systems and/or individual parts.

Step 2. Document the interactions between elements: strengths of relationships between the elements are described. The relationship tables can be used in this step.

Step 3. Cluster the elements into modules: the system is decomposed into a set of modules. The process before this step is the same as the process using the original DSM approach. The defined modules at the first iteration of the process are the same as the modules defined using the original DSM approach, but the modules can be changed through the iteration of the loop. After the final iteration of the process, the modules at this step can consider the relationships between elements and the relationships between functional requirements and elements.

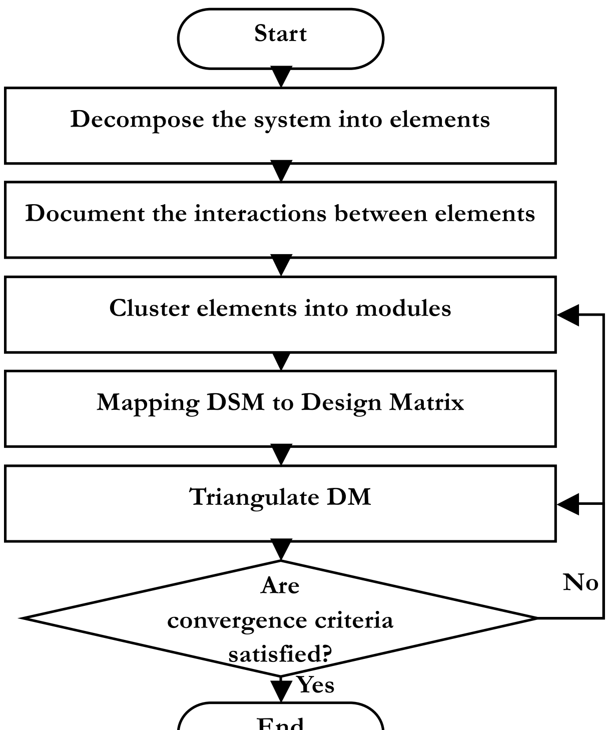


Figure 4. Decomposition process using axiomatic design and DSM

Step 4. Mapping DSM to the axiomatic design matrix: axiomatic design and DSM are linked. In this step, the relationship tables of step 2 are used to express functional requirements of the system and to select design parameters corresponding to each functional requirement. After the expression of functional requirements and selection of design parameters, the axiomatic design matrix is constructed based on these functional requirements and design parameters.

Step 5. Triangulate axiomatic design matrix: the independency of the functional requirements is checked from the viewpoint of modules which are defined at step 3.

Step 6. If the system satisfies the Independence Axiom of axiomatic design [Suh, 1990, 2000], the modules are fixed and the process is terminated. If the system does not satisfy the Independence Axiom, unfortunately, the modules should be redefined in step 3 and the process continues until the system satisfies the Independence Axiom.

The modules defined through the proposed process can consider physical and logical relationships between elements, and relationships between functional requirements of the system and elements simultaneously. The design procedure of the system with defined modules and the design procedures of the modules with constituent elements can be defined according to axiomatic design. And the defined modules also have merits for manufacturing and assembling of the system because the modules inherit the strengths of the DSM.

4 DECOMPOSITION OF A MOUNT TYPE HVAC SYSTEM

The proposed method is applied to a mount type HVAC system. A mount type HVAC system is a type of HVAC system which is installed between a ceiling and ceiling boards. Because the mount type HVAC system takes minimum space in the room and can control the climate of the room, the market share of this mount type HVAC system is gradually increasing these days.

There are already decomposed modules of the mount type HVAC system and the modules are defined using the original DSM approach. The HVAC system was decomposed with about seventy elements which consist of sub-assemblies and/or individual parts, because the modules should be decomposed at the assembly level of the air-conditioner. The relationships between elements are defined according to five interaction types: spatial, information and so forth. After the clustering of the constructed DSM, ten modules are defined to consider the relationships between components.

In this paper, the proposed decomposition method is verified with the existing defined modules using the original DSM approach. The verification was started at step 4, because there was a clustered DSM of the air-conditioner. Relationship tables were made to define the functions of the elements and to quantify the relationships between the elements, and one of the relationship tables is shown in Table 2. Interviewing and surveying of engineering members and experts are performed and performance estimation software is used to make the relationship tables. About eighty functional requirements are defined based on the contents of the relationship tables and design parameters corresponding to each functional requirement are selected within the air-conditioner. The axiomatic design matrix was obtained based on the defined functional requirements and design parameters, and the matrix is shown in Figure 5.

From the axiomatic design matrix in Figure 5(b), independences of functional requirements between the defined modules can be found. The design procedure of the system with defined modules, moreover, can be defined, and the design processes of the modules with constituent elements also can be defined from the axiomatic design matrix in Figure 5(b).

5 CONCLUSIONS

In this paper, a new decomposition method is presented to define rational modules considering relationships between elements, and between functional requirements of the system and elements. To define the rational modules, axiomatic design and design structure matrix (DSM) is linked through the implicitly existed functional requirements in the DSM. The proposed decomposition method is applied to the A mount type HVAC system and the defined modules are analyzed. From the axiomatic design matrix obtained during the process, the design procedure of the system and the design processes of the modules are defined to design the system efficiently based on axiomatic design.

Although the proposed decomposition method can define rational modules of the system, so far, it only can be adopted to existing systems. In many cases, the modules should be defined during the early stage of a design process of a new system. In this viewpoint, further development of the proposed method is required for the design of the new system.

6 ACKNOWLEDGEMENTS

This work was supported by Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government (MEST) (No. R01-2008-000-10012-0) and the authors are thankful to Mrs. MiSun Park for her correction of the manuscript.

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Table 2. An example of a relationship table for the mount type HVAC system

Elements	Thermal sensor and Control system			
Function (Thermal sensor)	A thermal sensor measures the room air temperature at the inlet of the air-conditioner.			
Function (Control system)	Control system determines which functions should be turned on and/or off.			
Relationship:	A thermal sensor provides room temperature information to the control system.			
Score:	Spatial:	0	Energy:	0
	Information:	+2	Materials:	0

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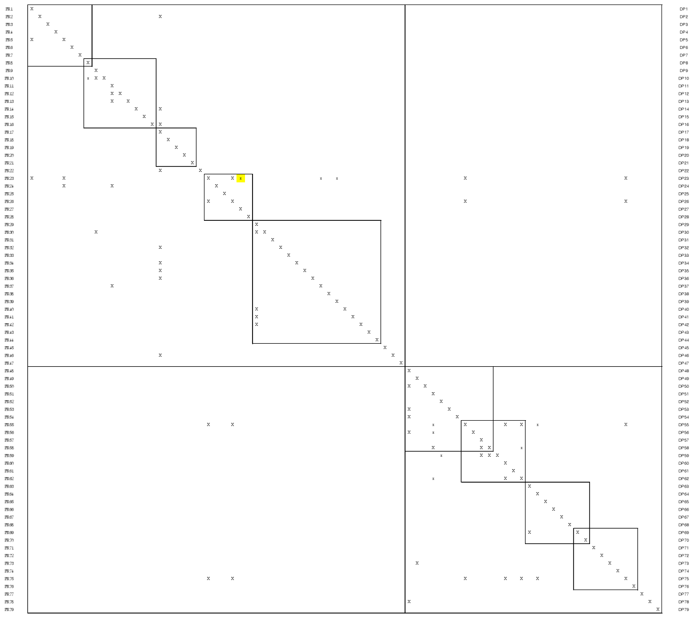
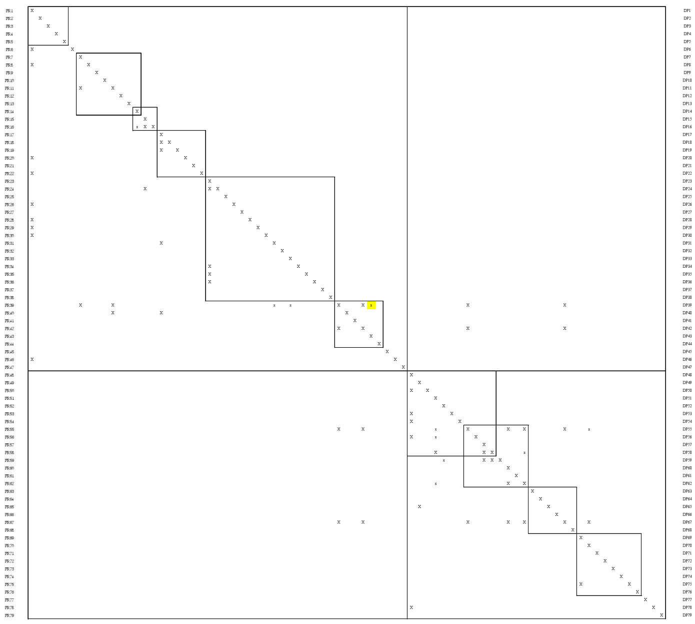


(a) Constructed axiomatic design matrix



(b) Triangulated axiomatic design matrix

Figure 5. Axiomatic design matrix of the ceiling type air-conditioner