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MODULAR DESIGN METHOD USING THE INDEPENDENCE AXIOM AND DESIGN STRUCTURE MATRIX IN THE CONCEPTUAL AND DETAILED DESIGN STAGE

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ABSTRACT

Recently, the modular design of products has become increasingly popular in modern engineering design because of the various benefits of modular products. These benefits include reduced cost, rapid product development and reduced production time. However, in many cases, the modules might have contradictions from the viewpoint of the Independence Axiom because the modules are defined based on the physical relationships among components of the product. On the other hand, modules which do not have contradictions can be defined using axiomatic design theory but the physical relationships are not considered in this case. The modules, therefore, may need additional treatment to implement in real product design because the physical relationships among components are important in real product design. To overcome the difficulty of modular design, a new design method is proposed to design a modular product based on relationships among functional requirements (FRs) and physical relationships among design parameters (DPs) of the product. Axiomatic design and the design structure matrix (DSM) are efficiently combined in the proposed method. FRs and DPs are defined based on the Independence Axiom of axiomatic design and the zigzagging process of axiomatic design is employed for the decomposition of FRs and DPs. After the decomposition, modules are defined using DSM to modularize the DPs at the bottom level of the zigzagging process. A design example is demonstrated to validate the proposed method. The results are discussed and the usefulness of the proposed method is presented.

Keywords: modular design, Design Structure Matrix (DSM), function-based design.

1 INTRODUCTION

Engineering design can be defined as a process which determines the working principles, components, size and dimensions of a product and evaluates the performances of the product [Haik, 2003]. Engineering design can be grouped into three stages such as conceptual design, preliminary design and detailed design based on the activities involved in each stage. Sometimes engineering design can be divided into conceptual design and detailed design [Ullman, 2003; Park, 2007]. Conceptual design is carried out at the earliest stage of engineering design and the most important decisions including the overall functional requirements and characteristics of a product are determined in this stage. Sizes and shapes of components, on the other hand, are determined in the detailed design stage using numerical analyses and experiments.

Engineering design, also, can be grouped into original design, adaptive design and variant design, or original design, redesign, configuration design, selection design and parameter design according to the intention at the beginning of the design [Pahl and Beitz, 1984]. Variant design, which determines a new design by changing dimensions and shapes, includes redesign and parameter design. Adaptive design, on the other hand, includes selection design and configuration design. Original design is a design process which generates innovative and unconventional products or systems. Conceptual design is usually conducted at the original design stage.

Although relatively less time and cost are used in the conceptual design stage, the decisions which are made at this stage affect all of the following decisions and processes of the product design. The impact of the design decisions in the latter design stages such as detailed design is not large, but the wrong design decisions during the conceptual design stage can cause a major defect in the product. According to these important characteristics of conceptual design, research about design methods and/or methodologies of the conceptual design is an important research area of engineering design.

There is some research about the conceptual design stage and this research can be classified into solution-oriented methods and problem-oriented methods. Solution-oriented methods are heuristic methods which focus on finding solutions. Brainstorming and synectics are the most popular design methods of the solution-oriented methods. Problem-oriented methods, on the other hand, are systematic methods which focus on the design problems and try to figure out the characteristics of the product. Problem-oriented methods include Axiomatic Design [Suh, 2001, 2005, 1995; Lee, 2003; Do and Park, 2001] and the function-based design method [Ullman, 2003; Pahl and Beitz, 1984; Hubka, 1982; Cross, 1994; Ulrich and Eppinger, 2008; Stone and Wood, 2000].

Solution-oriented methods depend on the abilities of designers because solution-oriented methods guide designers to generate a conceptual design by increasing the designer's creativity and/or avoiding stereotypical thinking. Solution-oriented methods are sometimes helpful but the design results may vary by the experience, intuition and characteristics of the designers [Goel, 1984]. Moreover, solution-oriented methods do not guarantee a solution. These difficulties are the reason why conceptual design is considered to be an art which is mainly affected by creativity and intuition.

Problem-oriented methods, on the other hand, guide designers to generate a conceptual design using systematic approaches. Most of the problem-oriented methods such as axiomatic design and the function-based design method propose a similar approach to generate a conceptual design. The approaches adopt the same scheme which divides a large design problem into manageable small sub-problems and then searches for solutions to the sub-problems. Designers can obtain a conceptual design by summing the solutions of the sub-problems in axiomatic design and the function-based design method.

Although the proposed systematic approaches of axiomatic design and the function-based design method are useful in the conceptual design stage, the two design methods have some difficulties in generating conceptual designs. Axiomatic design theory provides some guidelines to designers, but its success depends on the designer's ability to define the sub-problems. On the other hand, the function-based design method requires knowledge about the final solution of the conceptual design problem. Designers, therefore, can define sub-problems based on the knowledge about the potentially determined concept design.

A new concept design method is proposed in this research to overcome the difficulties of the current conceptual design methods. Axiomatic design and the function-based design method are combined to overcome the difficulties of each method. The proposed method uses a similar scheme which divides a large conceptual design problem into small manageable sub-problems. However, the difficulties of axiomatic design and the function-based design method are overcome by combining the zigzagging process of axiomatic design and the function-based design method. Moreover, the Design Structure Matrix (DSM) is adopted and combined in the proposed method to define modules and parts considering the manufacturing process of the product.

The proposed design method is expected to generate a conceptual design using systematic processes. Moreover, the obtained conceptual design has modular parts and modules which can be used in the manufacturing process of the product. The proposed design method is adopted to design some examples to validate the method and the results are discussed.

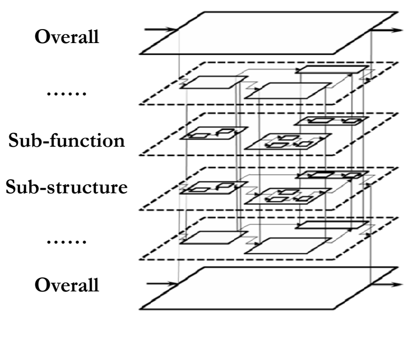


Figure 1. Design procedure of a function-based design method.

2 BACKGROUND THEORIES

2.1 FUNCTION-BASED DESIGN METHOD

The function-based design method is one of the well-known design methods in the conceptual design stage. The function-based design method of Pahl and Beitz [1984] and Hubka [1982], which represents European design research, has spawned many variant methods by N. Cross [1994], D. Ullman [2003], K. Ulrich and S. Eppinger [2005], and R. Stone and K. Wood [2000]. Regardless of the variations in the methods, all function-based design methods begin by formulating the overall function of a product. Then, the overall function is decomposed into small, easily solved sub-functions. A conceptual design can be obtained by defining sub-structures which satisfy the corresponding sub-functions and then summarizing the defined sub-structure into an overall structure. The design process of the function-based design method is shown in Figure 1.

In the function-based design method, conceptual design starts by creating a black box model, which is a graphical representation of a product function with input/output flows of the materials, energy and signal as shown in Figure 2. Although axiomatic design does not consider the flows of the materials, energy and signal explicitly, the function-based design method uses the flows to generate a concept design. Input and output flows of the black box are defined based on the customer needs.

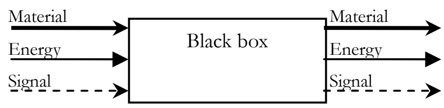


Figure 2. Black box system model

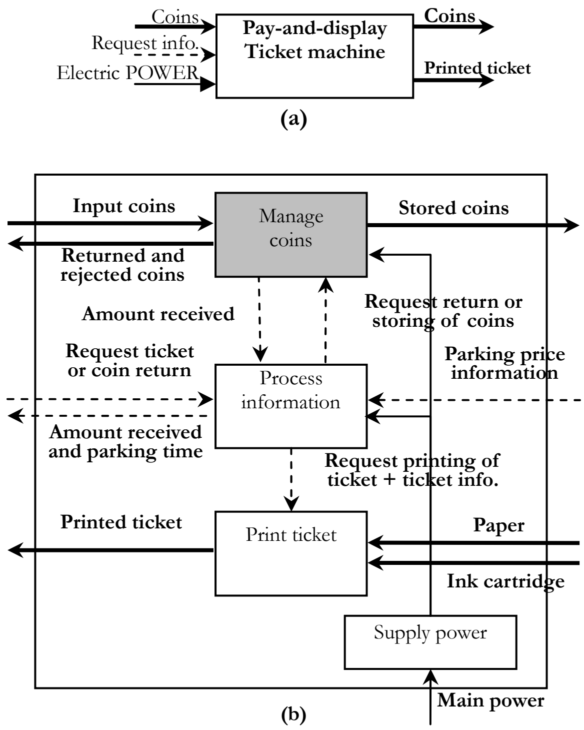


Figure 3. Example of a pay-and-display ticket machine.

An example of a black box model for a pay-and-display ticket machine is shown in Figure 3(a). The overall function of the pay-and-display ticket machine is then decomposed into sub-functions considering flows as shown in Figure 3(b). A defined sub-function can be decomposed into more levels of detail until the sub-functions are simple enough to solve easily. The decomposed functions are connected with materials, energy and signals just like a network diagram. The network diagram is called a function structure. After the decomposition of functions, sub-structures which satisfy the corresponding sub-functions should be selected. And then a conceptual design can be obtained by summing the selected sub-structures into an overall structure.

In the function-based design method, each sub-function should be expressed as a verb-object pair. It is very similar to the functional requirements of axiomatic design which is defined by an imperative sentence. Because the function is defined as a description of an operation to be performed by a product, a function and sub-function of the function-based method is identical to the functional requirement of axiomatic design. Moreover, because a structure is selected to satisfy the corresponding function, structure and sub-structure of the function-based method, this is identical to the design parameter of axiomatic design.

Although the function-based design method provides a systematic technique to design a product, the design method has some limitations in the conceptual design stage. First, a function cannot be decomposed in a useful way without being guided by the knowledge of existing solutions. The defined structure which is selected to satisfy the corresponding function may have critical contradictions. This means that a structure can have a negative effect on the other functions. It is the same concept as the coupled design of axiomatic design. To adopt the function-based design method at the conceptual design stage, these limitations are removed by combining axiomatic design and the function-based design method in this research.

2.2 DESIGN STRUCTURE MATRIX

"The Design Structure Matrix (DSM) is a popular representation and analysis tool for system modeling, especially for the purposes of decomposition and integration. 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 Table 1 [Sosa *et al.*, 2000; Steward, 1991; Browning, 2002]." [Hong and Park, 2009]

"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 [Sosa *et al.*, 2000] and the process is shown in Figure 4." [Hong and Park, 2009]

"A component-based DSM documents interactions among elements in a system architecture. The number and definitions of the interaction types can be different based on the given design problem. The interactions should be quantified to describe the strengths of the relationships between the elements. The quantification can be different based on the design problems. 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 a genetic algorithm (GA), fuzzy logic, distance penalty algorithm [Rissanen, 1983], and so forth. Figure 5 illustrates an example of the component-based DSM of a climate control system of an automobile researched by Sosa *et al.* [2000]." [Hong and Park, 2009]

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

Table 1. Four Types of DSM.

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

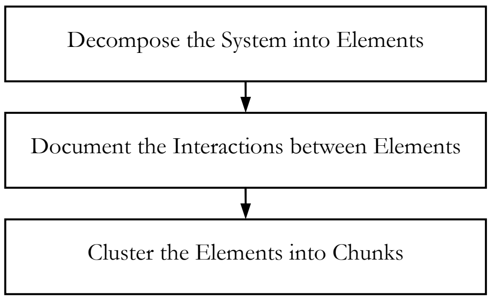
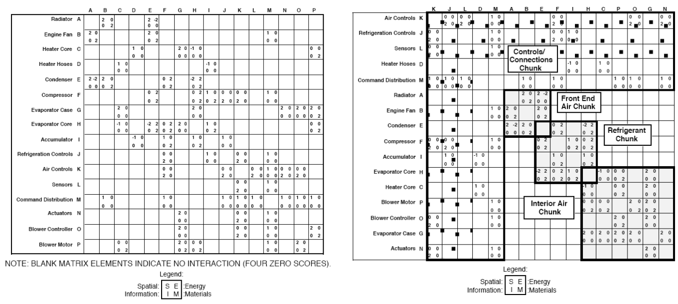


Figure 4. Decomposition process of component-based DSM.



(a) DSM of a climate control system example

(b) Clustered DSM of a climate control system example

Figure 5. DSM example for an air-climate control system of an automobile (adopted from Sosa *et al.* [2000]).

can consider the relationships between the functions and elements is required." [Hong and Park, 2009]

3 CONCEPTUAL DESIGN METHOD

3.1 CONCEPTUAL DESIGN METHOD USING THE AXIOMATIC DESIGN THEORY AND FUNCTION ANALYSIS MODEL

In axiomatic design theory, hierarchies are generated by the zigzagging process. The functional requirements of the sub-level are determined by the characteristics of the design parameter in the upper-level and the design parameters of the sub-level are selected to satisfy the corresponding functional requirements at the same level in the zigzagging process. The zigzagging process explains that the sub-level functional requirements should be decomposed by considering the upper-level design parameter, but does not explain how the sub-level functional requirements can be decomposed considering the upper-level design parameter. Currently, sub-level functional requirements are decomposed based on the designer's knowledge and experiences. Therefore, it is difficult for a designer to design a product using the axiomatic design theory in the conceptual design stage. A decomposition strategy, therefore, is required for conceptual design using the axiomatic design theory.

In the function-based design method, upper-level functions are also decomposed into sub-level functions. Because functions are decomposed based on the relationships and flows of materials, energy and signals of the product, decomposition of functions is more objective and systematic then the axiomatic design theory. Sub-level functions are decomposed based only on the upper-level function. However, the decomposition process of the function-based design method has two problems. First, to decompose a function into sub-level functions, designers should have some idea about the product [Chakrabarti and Bligh, 2001]. That means the decomposition process of the function analysis model can be performed with the product implicitly. Because a designer does not have information about the final product in the conceptual design stage, there are some difficulties to adopt the function-based design method at this stage. And then, the decomposed sub-level functions may contain contradictions which can make the product difficult to design [Hubka, 1982]. Because of these two problems, the function-based design method is difficult to adopt at the conceptual design stage.

In this research, the two conceptual design methods are combined to overcome the difficulties of the two design methods. The zigzagging process of the axiomatic design theory and the function analysis technique, which uses relationships and flows of materials, energy and signals among the functions, of the function-based design method are combined to decompose the functional requirements and the Independence Axiom is utilized to define the design parameters to satisfy the decomposed functional requirements. As mentioned earlier, the functions of the function-based design method are requirements which should be satisfied by the product and the structures are physical objects which satisfy the defined functions. The functions, therefore, can be considered as functional requirements and structures can be considered as the design parameters of the axiomatic design theory.

The schematic drawing of the proposed design method is shown in Figure 6. First, the functional requirements on the top level should be defined. Relationships among the functional requirements are considered based on the same techniques of the function-based design method in this stage. Design parameters then are selected to satisfy the corresponding functional requirements on the same level. The Independence Axiom should be satisfied at this stage. After the top-level design parameter selection, the sub-level functional requirements are defined based on the characteristics of the defined top-level design parameters and the relationships among the functional requirements from the viewpoint of materials, energy and signals. These processes continue until the bottom level is reached.

In the proposed method, the difficulty of the axiomatic design theory which depends on the designer's knowledge and experiences to decompose a functional requirement can be resolved by using the relationships and flows of materials, energy and signals of the function analysis model. One difficulty of the functional analysis method which needs information of the final product can be overcome by using the zigzagging process of the axiomatic design theory. And the other difficulty of the function-based design method, which may contain contradictions among decomposed functions, can be resolved by adopting the Independence Axiom of the axiomatic design theory.

3.2 DECOMPOSITION METHOD IN CONCEPTUAL DESIGN

Because the definition of functional requirements and the generation of design parameters which satisfy the corresponding functional requirements is the most important part of concept design, most design methods propose techniques and/or guidelines to generate functional requirements and design parameters systematically during the conceptual design stage. The proposed conceptual design method, as explained in the previous section also proposes a functional requirement definition technique and a design parameter generation technique by combining the axiomatic design theory and the function-based design method. Hierarchies of functional requirements and design parameters

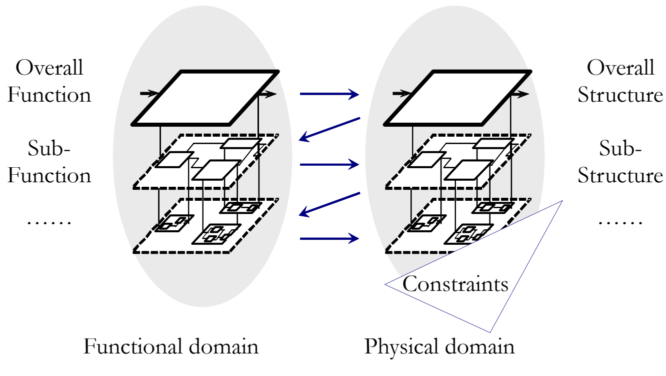


Figure 6. Concept design method using axiomatic design and the function-based design method.

and relationships among the functional requirements and design parameters can be obtained from the proposed method. The final concept design can be obtained by composing the generated design parameters but how to construct a physical object by composing the design parameters still remains as a problem to finalize the concept design. It is not only a problem of the proposed design method but also a problem of most existing design theories.

In this research, the Design Structure Matrix (DSM) is adopted to overcome the presented problem. Generally, DSM is used to define modules of a product using interactions among parts and components in the product. If design parameters can be grouped as modules using DSM, then a physical object can be constructed using design parameters more easily in the concept design stage. Although DSM has this excellent characteristic to construct a physical object, DSM is not adopted at the conceptual design stage because interactions among parts and components of a product are required to define modules. However, the proposed design method in the previous section can be linked with DSM because the method uses the function-based design method to decompose functional requirements.

In the function-based design method, functional requirements are decomposed based on the relationships among the functional requirements. The relationships can vary by product but are generally defined from a viewpoint of materials, energy and signals in the function-based design method. The network diagram of Figure 7 shows the relationships of a product which is decomposed with the function-based design method. Figure 7(a) shows the relationships among the functional requirements and Figure 7(b) shows the relationships among the design parameters which satisfy the corresponding functional requirements of Figure 7(a). Because the design parameters are selected to satisfy the corresponding functional requirements, the network diagram of design parameters of Figure 7(b) has same the relationships of the network diagram of functional requirements.

The types of relationship of the function-based design method are very similar to the types of interaction of DSM.

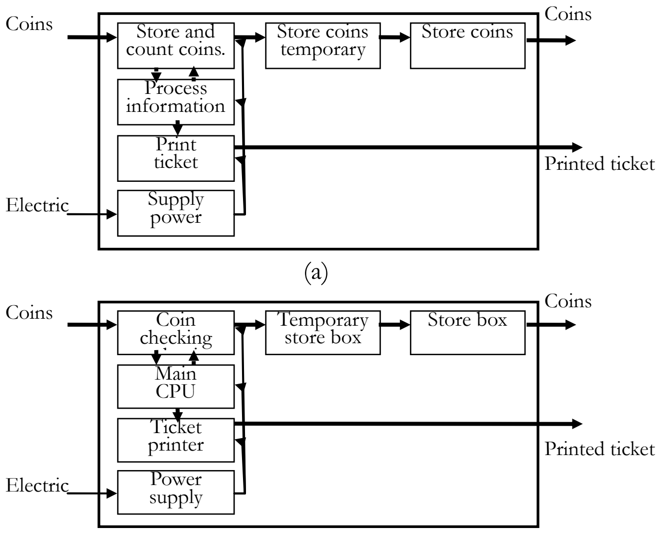


Figure 7. Example of a function structure.

The types of interaction for DSM also can vary with products but generally spatial, materials, energy and signal interactions among components are used in DSM. And the meaning of the relationships of the function-based design method and the interactions of DSM are nearly the same as well. Therefore, the meaning of the network diagram of the function-based design method can be considered as identical to the meaning of DSM. To compare the network diagram of the function-based design method and DSM, the network diagram of Figure 7(b) is transformed to a square matrix form as shown in Figure 8(a). The square matrix of Figure 8(a) is called a precedence matrix and shows the relationship among elements of the network diagram [Chakrabarti and Bligh, 2001]. The matrix representation of the network diagram can be considered as a DSM because the matrix contains the same information and has the same matrix form. The square matrix of Figure 8(b) can be obtained by clustering the matrix of Figure 8(a). The elements in the bold lined rectangular can be a module or part for the product and three modules and/or parts are obtained in Figure 8(b).

In this research, the concept design method of the previous section is linked to DSM to construct physical objects based on the concept design. Although a concept design can be obtained from the proposed design method, construction of a physical object based on the concept design is a totally different problem. To construct a physical object, DSM is adopted as shown in Figure 9. The bottom level network diagram which consists of design parameters and the relationships between them are used to generate a DSM and clustering of the DSM is performed to define modules and parts of a physical object. The physical object can be obtained with the defined modules and parts more easily and systematically with the proposed design method and DSM.

3.3 Design Procedure of the Proposed Method

A concept design can be generated by the following steps and the process is shown in Figure 10.

Step 1. Define functional requirements of the top-level based on the relationships among functional requirements from the viewpoint of materials, energy and signals

Step 2. Define design parameters which satisfy corresponding functional requirements of the same level. The Independence Axiom should be satisfied in

	1	2	3	4	5	6
1		1 0 0		1 0 0		0 0 1
2			1 0 0	0 1 0		0 0 1
3		1 0 0				
4	0 1 0	0 1 0			0 1 0	0 0 1
5				0 1 0		0 0 1
6	0 0 1	0 0 1		0 0 1	0 0 1	

(a)

	2	1	3	4	5	6
2		1 0 0	1 0 0	0 1 0		0 0 1
1	1 0 0			1 0 0		0 0 1
3	1 0 0					
4	0 1 0	0 1 0			0 1 0	0 0 1
5				0 1 0		0 0 1
6	0 0 1	0 0 1		0 0 1	0 0 1	

(b)

Figure 8. DSM constructed using a function structure.

this stage.

Step 3. Decompose the sub-level functional requirements based on the characteristics of the defined upper-level design parameters. Relationships among functional requirements from the viewpoint of materials, energy and signals are should be considered in this step.

Step 4. If the bottom level of the hierarchy is reached, then go to Step 5. Otherwise go back to step 2.

Step 5. Generate the DSM using the bottom level design parameters and relationships among them.

Step 6. Cluster the generated DSM to define modules and parts.

Step 7. Construct a physical objective using the defined modules and parts.

The proposed design method adopts the axiomatic

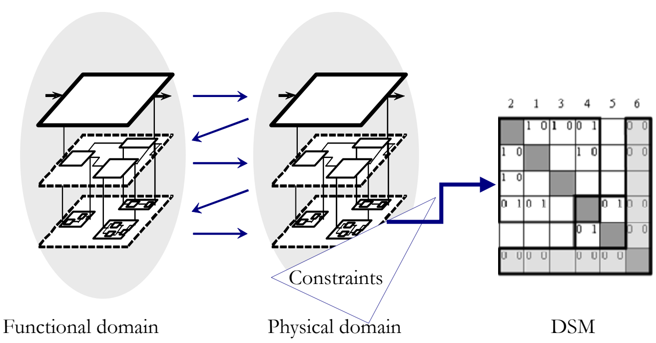


Figure 9. Concept design method using axiomatic design, the function-based design method and DSM.

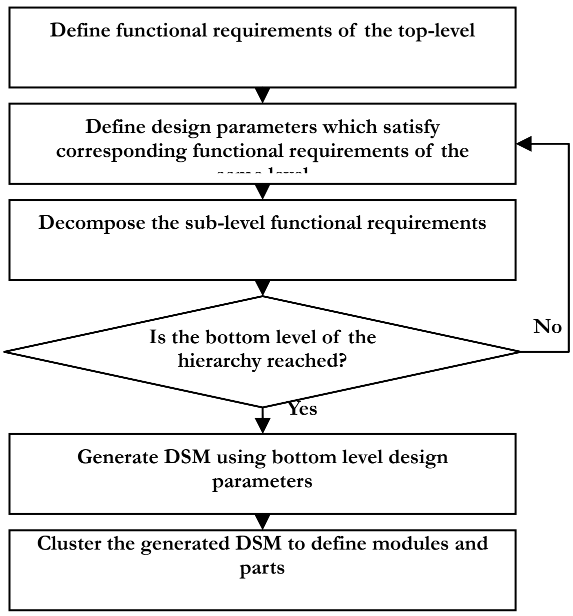


Figure 10. Procedure of the proposed design method.

design theory, the function-based design method and DSM to generate a concept design and to construct a physical object based on the concept design. Because independence among functional requirements and design parameters remains during the conceptual design process, the product can be designed systematically without feedback.

4 DESIGN EXAMPLE: DESIGN OF THE TILT MECHANISM OF A STEERING COLUMN

The steering column is a part of an automobile in which the drivers can control the moving direction of the automobile. It is connected with the steering wheel and an intermediate shaft as shown in Figure 11. The main function of the steering column is to transmit torque from the driver to a rack and pinion but the most complicated part of the steering column is the tilt mechanism part. The tilt/telescopic mechanism enables the drivers to change the steering wheel up/down and in/out position for the driver's convenience as shown in Figure 12. Although there is a tilt/telescopic column, the tilt column is generally used in most automobiles.

In this paper, the tilt mechanism of a steering column is selected as a concept design example. To change the up/down position of a steering wheel, human force is selected to input the tilt mechanism. The black box model of the tilt mechanism, therefore, is created as shown in Figure 13 and top-level functional requirements are defined as follows:

FR_1: Release/restrain the tube assembly.
FR_2: Control the up/down position of the tube assembly.
FR_3: Fix the tube assembly.

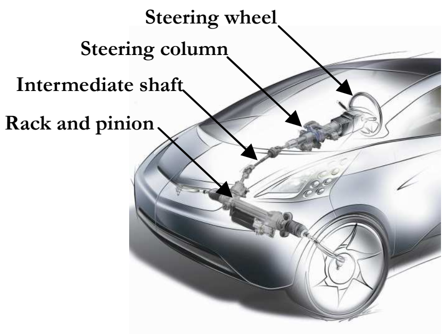


Figure 11. Steering column in an automobile.

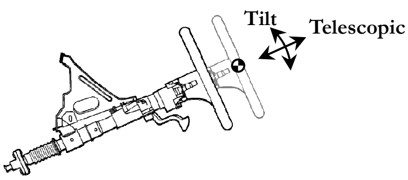


Figure 12. Tilt/telescopic steering column

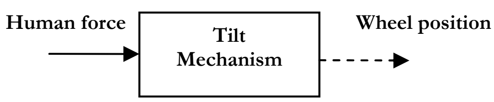


Figure 13. Black box model of a tilt mechanism.

To satisfy the corresponding functional requirements, the design parameters are selected as follows:

DP_1: Vertical displacement generation mechanism
DP_2: Rotatable mounting fixture
DP_3: Frictions between plates

The design equation is as follows:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & O & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (1)$$

Because the presented decomposition of the tilt mechanism is not enough to generate a concept design of the steering column, sub-level functional requirements should be decomposed considering upper-level design parameters. The function-based design method scheme is utilized to decompose the sub-level functional requirements. The sub-level functional requirements are decomposed considering relationships, human force and wheel positions as shown in Figure 14 and the sub-level functional requirements are defined as follows:

FR_{11}: Transfer the torque from human to the left and right side of the mechanism.

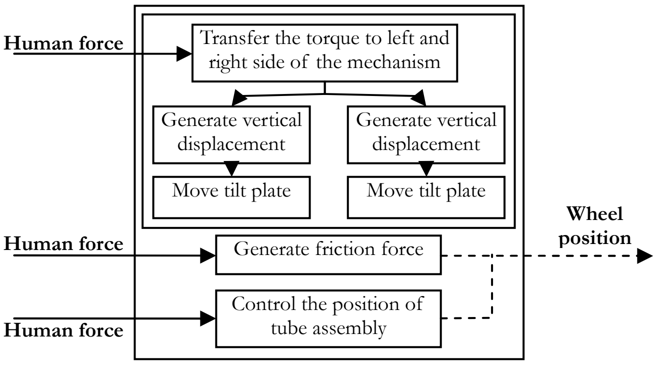


Figure 14. Detailed function structure of the tilt mechanism.

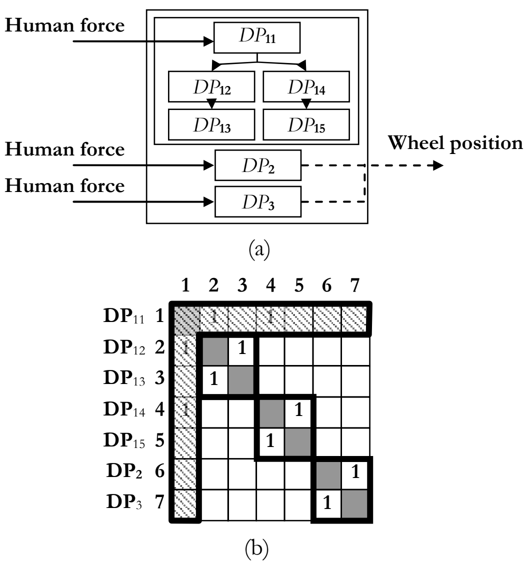


Figure 15. DSM of the steering column.

FR_{12}: Generate vertical displacement at the left side.
FR_{13}: Move the tilt plate at the left side.
FR_{14}: Generate vertical displacement at the left side.
FR_{15}: Move the tilt plate at the right side.
FR_2: Control the up/down position of the tube assembly.
FR_3: Fix the tube assembly.

To satisfy the decomposed functional requirements, corresponding design parameters are selected as follows:

DP_{11}: Shaped lever
DP_{12}: A bolt and nut (left side)
DP_{13}: Shaped mounting plate (left side)
DP_{14}: A bolt and nut (right side)
DP_{15}: Shaped mounting plate (right side)
DP_2: Rotatable mounting fixture
DP_3: Frictions between plates

And the design equation of the steering column is as follows:

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \\ FR_{14} \\ FR_{15} \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O & O \\ O & X & O & O & O & O & O \\ O & X & X & O & O & O & O \\ O & O & O & X & O & O & O \\ O & O & O & X & X & O & O \\ O & O & O & O & O & X & O \\ O & O & O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \\ DP_{14} \\ DP_{15} \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (2)$$

Using the function structure of the bottom-level as shown in Figure 15 (a), a DSM is constructed and clustered as shown in Figure 15(b). Figure 15(b) shows that DP_{12} and DP_{13}, DP_{14} and DP_{15}, and DP_2 and DP_3 have strong relationships among them. Because DP_{11} has a relationship with many design parameters, DP_{11} is difficult to group with any other design parameters. Based on the clustering result, it seems that DP_{12} and DP_{13}, DP_{14} and DP_{15}, and DP_2 and DP_3 are better grouped as a module. Based on the presented results, the concept design of the tilt mechanism can be obtained as

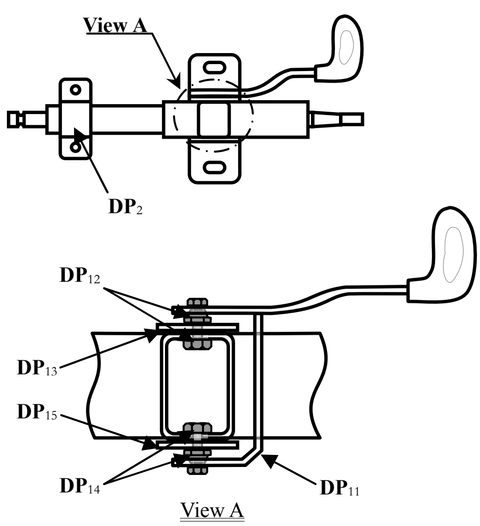


Figure 16. A schematic drawing of a steering column concept design.

shown in Figure 16. The design results seem reasonable but the module which consists of DP_2 and DP_3 seems impossible to group as a physical object in a real product.

5 CONCLUSIONS

In this research, a new design method is proposed to generate a concept design systematically in the conceptual design stage. Axiomatic design, the function-based design method and the Design Structure Matrix are adopted in the proposed design method. The zigzagging process and the Independence Axiom of axiomatic design and the function-based design method are combined to generate hierarchies of functional requirements and design parameters. DSM is also adopted to construct modules easily using the hierarchy of the design parameters. The proposed design method is expected to improve the concept design results by reducing human error, and providing a proper process and sequence in the conceptual design stage.

The proposed design method is verified with a tilt mechanism of the steering column. A new tilt mechanism of the steering column is generated using the proposed design method. However, in the steering column example, there is one module which seems impossible to combine with a physical object. It seems that the generated DSM does not contain any information about spatial relationships among the design parameters. Further researches about how to consider the spatial information in the concept design is needed.

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