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ANALYSIS OF A MOUNT TYPE HVAC CONTROL SYSTEM USING AXIOMATIC DESIGN

Se-Jung Lee
Seizetd04@hanyang.ac.kr
Department of Mechanical Engineering
Hanyang University
17 Haengdang-dong
Seoul 133-791, Korea

Eul-Pyo Hong
uphong@hanyang.ac.kr
Department of Mechanical Engineering
Hanyang University
17 Haengdang-dong
Seoul 133-791, Korea

Gyung-Jin Park
gjpark@hanyang.ac.kr
Department of Mechanical Engineering
Hanyang University
1271 Sa 3-dong , Ansan City,
Gyeonggi-do 425-791, Korea

ABSTRACT

The mount type HVAC control system is a type of HVAC control system which is installed between a ceiling and the ceiling boards of a room to control room temperature. Although the device is quite popular, design is conducted by a conventional way where engineering intuition and experiences are utilized. It is found that the design process is fairly inefficient and time-consuming because there are a lot of feedbacks. The axiomatic approach is used to investigate the design characteristics of the mount type HVAC control system and the Independence Axiom is utilized for the investigation. The overall hierarchy is established up to the level of components. It is found that the current design has many coupled and redundant aspects. The hierarchy is reorganized based on the Independence Axiom and a new design process is found. To exploit the new design process in practice, a design manual is made.

Key Words: Axiomatic design, Independence Axiom, A mount type HVAC control system

1 INTRODUCTION

A heating ventilating and air conditioning (HVAC) control system is an air conditioning machine to make a house comfortable by controlling the temperature of rooms. It is classified according to the installation place or position. A mount type HVAC control system is installed between a ceiling and the ceiling boards of a room. The main advantage is maximum utilization of living space [Song *et al.*, 1999]. Demand of the mount type HVAC control system is increasing.

The mount type HVAC control system is designed and manufactured according to various conditions such as the size of the installation place, the country, the environment, etc [Kim *et al.*, 2004]. The product design process has influence on the overall performance of the system, development costs and time [Park, 2007]. Currently, the mount type HVAC control system is designed with a somewhat regular process; however, most of the process is conducted in a conventional way where engineering intuition and experiences are utilized. Designers usually use knowledge which is not systematic. It is found that the design process is fairly inefficient and time-consuming because there are a lot of feedbacks [Lee *et al.*, 1996]. Therefore, it is difficult to identify the problems when product performance has some defects. Also, it is quite difficult to exchange views on product design between senior and junior designers.

This paper focuses on the rational and effective design process of the mount type HVAC control system. The axiomatic approach is used to investigate the design characteristics of the mount type HVAC control system and the Independence Axiom is utilized for the investigation. Axiomatic design is a framework for an effective design created by N.P. Suh. It gives good ideas for conceptual design as well as detailed design [Suh, 1990]. To propose the rational and effective design process of an existing mount type of the HVAC control system, the overall hierarchy is established up to the level of parts based on the axiomatic approach. The design matrix is defined and the order of the design process is proposed. Some coupling aspects of the existing product are found and the proposed design order minimizes the feedback processes. A design manual is made to utilize the proposed process for practical use.

2 AXIOMATIC DESIGN

Axiomatic design is a design methodology that was created by N.P. Suh [Suh, 1990]. It gives the standard of a good design in an objective and rational way. Design is defined as a continuous interplay between 'what we want to achieve' and 'how we want to achieve it.' 'What we want to achieve' is called functional requirements (FRs) and it is determined from customer needs. To satisfy the functional requirements, design parameters (DPs) must be selected by embodying in a physical domain. The design process involves relating these FRs in the functional domain to the DPs in the physical domain. In other words, design is defined as the mapping between the FRs and the DPs, through the proper selection of DPs that satisfy FRs. The mapping process depends on a designer's individual creative process. Therefore, there can be many good design solutions.

The domain and mapping are illustrated in Figure 1. The customer domain is characterized by the need that the customer seeks in a product. Based on this need, the design engineers define the FRs in terms of uniformity and also the constraints. And then, to satisfy the specified FRs, DPs are determined in the physical domain. Finally, to produce the product specified in terms of DPs, process variables (PVs) are defined in the process domain. FRs and DPs are decomposed into a hierarchy until designers get a complete detailed design or until the design is completed. A DP is determined by the

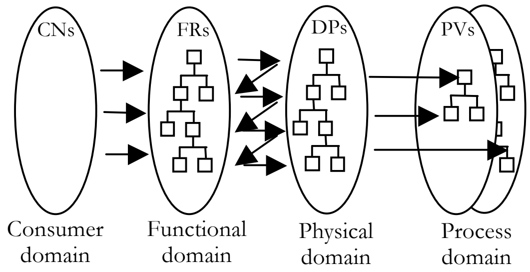


Figure 1. Concept of design, mapping and spaces

corresponding FR in the same level; and then, FRs in the sublevel are determined by the characteristics of the DP in the upper level. This process is called the 'zigzagging process.'

In axiomatic design, there are two design axioms. One is the Independence Axiom and the other is the Information Axiom. The Independence Axiom deals with the relationship between functions and physical variables, and the Information Axiom deals with the complexity of design. As mentioned earlier, design is defined as the mapping process between the FRs in the functional domain and the DPs in the physical domain. This relationship may be characterized mathematically as follows:

$$\{FR\} = [A]\{DP\} \quad (1)$$

The characteristics of the required design are represented by a set of independent FRs, these may be treated as a vector {FR} with m components. Similary, the DPs in the physical domain also constitute a vector {DP} with n components. $[A]$ is the design matrix which relates the components of the FR vector to the components of the DP vector. Design matrix [A] is written as

$$[A] = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mn} \end{bmatrix} \quad (2)$$

Each element A_{ij} of the matrix relates to a component of the FR vector to a component of the DP vector. In general, the element A_{ij} is expressed as

$$A_{ij} = \frac{\partial FR_i}{\partial DP_j} \quad (3)$$

Table 1 shows three cases of the design according to the characteristics of the design matrix. When the design matrix $[A]$ is diagonal, each of the FRs can be satisfied independently by means of one DP. Such a design is called an uncoupled design. When the design matrix is triangular, the independence of FRs can be guaranteed if and only if the DPs are determined in a proper sequence and such a design is called a decoupled design. If the design matrix is full, it is called a coupled design.

Based on the difference in the numbers of FRs-DPs, there are three cases of design such as ideal, redundant and coupled design in Table 2. When the number of FRs is equal to the number of DPs, the design is an ideal design, provided that the Independence Axiom is satisfied. When there are more DPs than FRs, the design is a redundant design. A redundant design may or may not violate the Independence Axiom. When the number of DPs is less than the number of FRs, either a coupled design results or the FRs cannot be satisfied. The Independence Axiom encourages an ideal design rather than a redundant or a coupled design. Therefore, when several FRs must be satisfied, designers must develop designs to create a diagonal or a triangular design matrix by exploiting the research.

The Information Axiom states that among all the designs that satisfy the Independence Axiom, the one with minimum information content is the best design [Do and Park, 2001]. Resources for the Information Axiom are available in the references. In this paper, only the Independence Axiom is utilized.

3 DESIGN OF THE MOUNT TYPE HVAC CONTROL SYSTEM USING AXIOMATIC DESIGN

3.1 CONVENTIONAL DESIGN PROCESS OF THE MOUNT TYPE HVAC CONTROL SYSTEM

An HVAC control system is a machine that regulates room temperature. A mount type HVAC control system is a type of the HVAC control system, which is installed between the ceiling and ceiling boards of a room to control temperature [Song *et al.*, 1999]. The basic principle of the mount type HVAC control system is absorbing heat in a room and emitting it to the outside of the room [Richard *et al.*, 1998]. Figure 2 illustrates the components of the mount type HVAC control system which consists of the indoor and outdoor machines.

Most of the HVAC systems employ the refrigeration cycle using refrigerant to generate the cool air in a room [Kim and Park, 1996]. Figure 3 presents the refrigeration cycle using the refrigerant. In the outdoor part, a compressor generates the flow of refrigerant and a condenser releases the heat. The

Table 1. Relationship between FRs and DPs

	Uncoupled design	Decoupled design	Coupled design
Design matrix	$\begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix}$	$\begin{bmatrix} A_{11} & 0 \\ A_{21} & A_{22} \end{bmatrix}$	$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$

Table 2. Ideal, redundant and coupled design

	Design equation
Ideal design	$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$
Redundant design	$\{FR_1\} = [A_{11} \quad A_{12}] \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$
Coupled design	$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} \\ A_{21} \end{bmatrix} \{DP_1\}$

indoor part consists of a capillary tube to control the flow of the refrigerant and an evaporator to absorb the heat in the room [Choi and Kim, 2005]. The refrigerant periodically circulates between the two sides so that the indoor heat is absorbed and released outside [Kim and Park, 1996]. Also, there are other components to activate the machine and maintain the operation of the mount type HVAC control system.

Currently, design is carried out based on the conventional process illustrated in Figure 4. Since the machine is not a new one, most of the design aspects are already known. Therefore, the designer selects appropriate components. First, positioning for installation between a ceiling and ceiling boards of a room is determined. It is the major factor for the performance of the machine. And the designer determines the components such as the refrigeration cycle and related ones to satisfy the positioning for installation. After that, performance tests are conducted to meet the performance requirements for the mount type HVAC control system. If the HVAC system satisfies the performance tests, the design process ends. Otherwise, the designer redesigns the components until the performance requirements are satisfied.

In the conventional design, the design of the HVAC system depends on the ability of the designer because the components are selected by the intuition and experiences of the designer. The flow of the conventional design process is illustrated in Figure 5. A module is defined as a large part composed of components. A module can be designed independently. Modules such as the refrigeration cycle, the air-flow, the drainage and control are designed and assembled.

The conventional way may be good when the product development is finished. However, the performance requirements are continuously changing according to the customer. Also the product should be designed and manufactured to satisfy the new conditions for the setting size, the country where the product is used, the environments, etc [Kim *et al.*, 2004]. In this case, the conventional way needs many trials and errors to meet the requirements because it is not easy to identify the relationships of components and their characteristics. Besides, the designer may have difficulties to find a rational design process to satisfy the new requirements. If engineering intuition and experiences are utilized, the designer may use tacit knowledge which is not systematized. Because the design is made personally in a subjective way, it is difficult to transfer the design knowledge of a senior designer to a junior designer.

3.2 AXIOMATIC DESIGN OF THE MOUNT TYPE HVAC CONTROL SYSTEM

As mentioned earlier, there are many difficulties in the conventional design process. To overcome the difficulties, a new design process is defined by using the axiomatic approach. Customer needs (CNs) are gathered first, FRs are defined based on the CNs, and DPs are selected to satisfy the independence of the FRs [Suh, 2001]. The FR-DP relationship is made by the design matrix and a hierarchy of the design process is made. It is noted that the hierarchy is made by decomposition of the FR-DP relationships up to the components as the bottom level. CNs are defined from the customer survey and interviews with design engineers. CNs are shown in Table 3.

Based on the CNs in Table 3, FRs and constraints (Cs) are

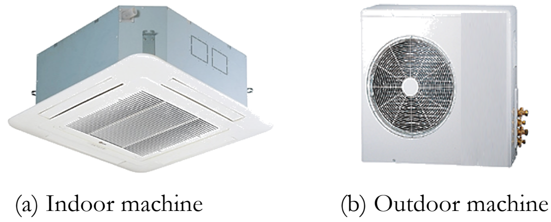


Figure 2. Indoor and outdoor machines

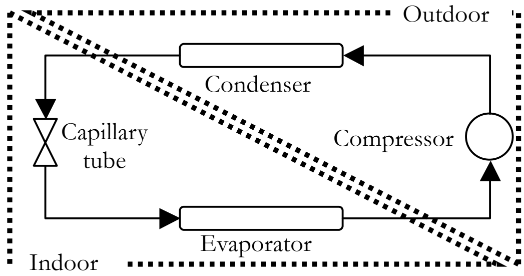


Figure 3. Composition of an HVAC control system

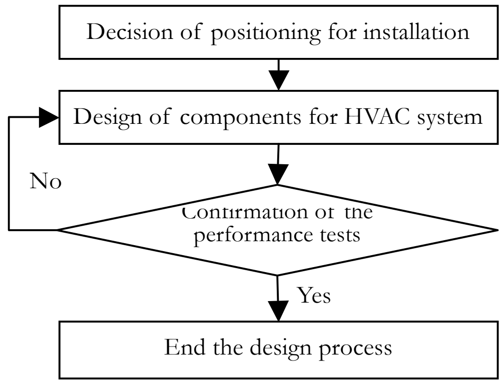


Figure 4. The conventional design process for an overall HVAC control system

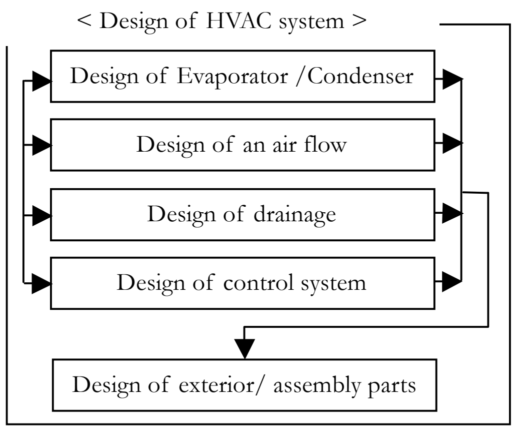


Figure 5. The conventional design process for design of part for HVAC system

defined at the top level. They are as follows:

FR_1 = Minimize a possessed space of the mount type HVAC control system.

FR_2 = Generate appropriate air current in the room.

FR_3 = Make enough cold air.

FR_4 = Minimize the vibration/noise of the mount type HVAC control system.

FR_5 = Maintain purity of the air quality in the room.

FR_6 = Control the temperature under user's directions.

FR_7 = Make maintenance and repair of the system easy.

They are overall functions required for the mount type HVAC control system. It is noted that the functions are defined based on the physical objects in the conventional design. They are refrigeration cycle, air-flow, drainage, control and assembly parts. The above FRs have two more functions such as ceiling installation and noise.

Constraints are defined as well. The constraints provide bounds on acceptable design solutions and differ from the FRs in that they do not have to be independent. It is generally defined from design specifications [Park, 2007]. Constraints are defined as follows:

C_1 = Satisfy the first-grade for energy efficiency.

C_2 = Satisfy related standards.

C_3 =Satisfy the product size to sufficiently insert the HVAC system between the ceiling and ceiling board.

C_4 = Minimize the production cost.

To meet FRs, an appropriate set of DPs are defined as follows:

DP_1 = Ceiling type structure

DP_2 = Air current formation system

DP_3 = Mutual assistance system

DP_4 = Vibration/noise reduction system

DP_5 = Air cleaner system

DP_6 = Temperature control system

DP_7 = Maintenance/repair system

From the FR-DP relationship, the design equation is defined as follows:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \\ FR_7 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 & 0 & 0 \\ 0 & X & X & X & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X & 0 & 0 \\ 0 & X & X & 0 & X & X & 0 \\ X & X & X & X & X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \\ DP_7 \end{Bmatrix} \quad (4)$$

where X represents the non-zero elements and O represents the zero elements. A non-zero element means that a DP has influence on the corresponding FR [Suh, 1990]. Since the matrix is triangular, the top level is a decoupled design. Therefore, independence of FRs is guaranteed if and only if the DPs are determined in a proper sequence.

3.3 Result of decomposition (hierarchy)

The FRs and DPs at the top level are decomposed by using the zigzagging mapping process. The decomposition is made until the bottom level for components is reached. Detailed explanation for the decomposition is omitted here. The entire design matrix is shown in Figure 6. The left column of the table represents the FRs and the upper row includes the corresponding DPs. The mount type HVAC control system has a decoupled design at the top level as shown in Equation (4); however, the entire design matrix is a non-square matrix as shown in Figure 6. The non-square matrix means that the current product has the characteristics of redundant and coupled designs [Suh, 2001]. In this research, an effort to fix those aspects is not made.

4 IMPROVEMENT OF THE DESIGN PROCESS AND PRACTICAL APPLICATION

4.1 Coupled aspects of the existing mount type HVAC control system

As mentioned earlier, the entire matrix is a non-square one. This means that some FR-DP relationships are coupled at some points of the hierarchy. In this section, the coupled parts are explained.

An FR is as follows:

FR_{222} = Generate the air-flow in the perpendicular direction using a rotary motion.

The existing system has five corresponding DPs as follows:

DP_{226}= The number of blades

DP_{227} = Ratio of the inside/external diameters

DP_{228} = An angle among blades

DP_{229} = Shape of the blade

DP_{2210} = Ratio of pitch/chord

The DPs are components of the turbo fan. [Chang *et al.*, 2002, Kim *et al.*, 2001]

The relationship between FR_{222} and DPs can be represented as

Table 3. Required conditions for a mount type HVAC control system

Customer needs from the general users	Customer needs from design engineers
People should feel cool. The room should be cooled as soon as possible. The cool air must sufficiently circulate. Uniform temperature is required. Each vane should be controlled separately. Temperature control should be easy. Control from a distance is required. The machine should operate quietly. Energy consumption should be minimized.	Dust or bad smell should be eliminated. The maintenance and management of the system should be easy. The system should need a small space and have an aesthetic outside shape. Regulations should be satisfied. Production costs should be minimized.

$$\{FR_{222}\} = [X \quad X \quad X \quad X \quad X] \begin{Bmatrix} DP_{226} \\ DP_{227} \\ DP_{228} \\ DP_{229} \\ DP_{2210} \end{Bmatrix} \tag{5}$$

Obviously, it is a redundant design and a lot of feedbacks are required [Park, 2007]. The redundant aspects are also found from the components parts such as the motor, the orifice, the fin of the evaporator and the condenser, the damper and the cabinet EPS.

There are other two coupled design cases when the number of DPs is less than that of FRs and the design matrix is a full matrix. The turbo fan, the cabinet EPS and the orifice have more FRs [Suh, 1990]. Also, the refrigerator cycle has more FRs. The refrigerator cycle consists of three subsystems such as the compressor system, the heat exchanger system and the capillary tube [Richard *et al.*, 2005]. The FRs and DPs for the compressor system are defined as:

FR_{31} = Generate the pressure to change the state of the refrigerant.

FR_{32} =Generate the air-flow for ability of air conditioning to sufficiently cool the room.

DP_{31} = Compressor system

The relationship is

$$\begin{Bmatrix} FR_{31} \\ FR_{32} \end{Bmatrix} = \begin{bmatrix} X \\ X \end{bmatrix} \{DP_{31}\} \tag{6}$$

Therefore, it is a coupled design. The capillary tube has a similar tendency.

The heat exchanger system has slightly different characteristics. The FRs, DPs and their relationships are as follows:

FR_{332} = Change refrigerant from gas to liquid.
FR_{333} = Change refrigerant from liquid to gas.
DP_{322} = Evaporator system
DP_{323} = Condenser system

$$\begin{Bmatrix} FR_{332} \\ FR_{333} \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{322} \\ DP_{323} \end{Bmatrix} \tag{7}$$

Since the design matrix in Equation is a full matrix, it is a coupled design. Therefore, the refrigerator cycle is a coupled design.

As mentioned earlier, the coupled design is not good from an axiomatic design viewpoint. The coupled design should be modified to a uncoupled design or decoupled design by selecting a different set of DPs [Shin and Park, 2006]. In this research, new DPs are not defined to modify the coupled design because of the sponsor's request. The design matrix shows where the designer should be careful.

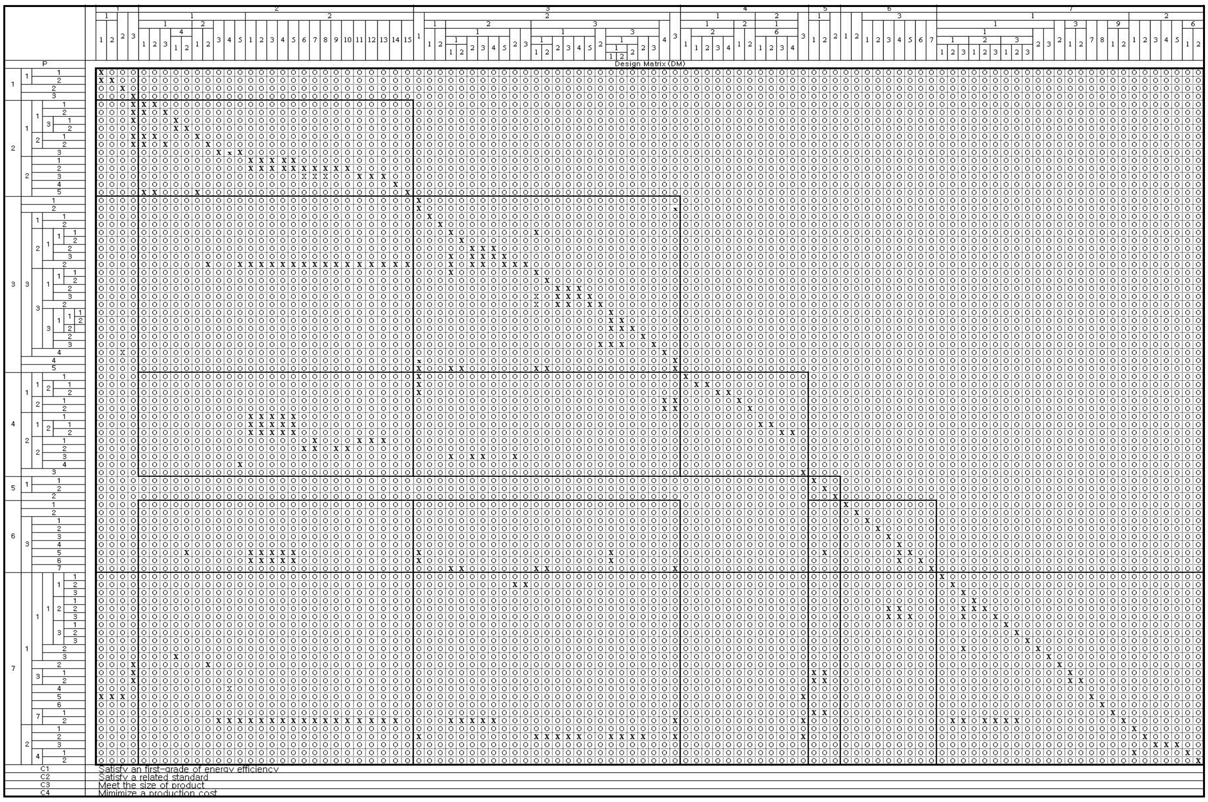


Figure 6. Entire design matrix

4.2 DESIGN FLOW

The conventional design process for a mount type HVAC control system has many problems to satisfy diverse demands. A design flow can be proposed based on the design matrix [Suh, 2001]. A module can be defined by a DP of the top level of the design hierarchy. The flow of the modules can be defined by the summation, control and feedback junction as illustrated in Figure 7. The summation junction is a simple summation of FRs and represents the flow for an uncoupled design. It connects parallel modules. The control junction represents the sequential control of DPs as suggested by the design matrix for a decoupled design. It links the modules sequentially. The feedback junction is for a coupled design. It requires feedback and violates the Independence Axiom [Suh, 1998].

The flow of the top level is illustrated in Figure 8 according to Equation (4). Because it is a decoupled design, the design flow at the top level links the modules sequentially. The flow from the entire design matrix has been made; however, it is omitted here. The improved design flow is a rational way compared to the conventional process where each module is independently designed. By showing the overall design flow of the mount type HVAC control system, it is easy for designers to understand the overall design process and junior designers can follow the design process easily.

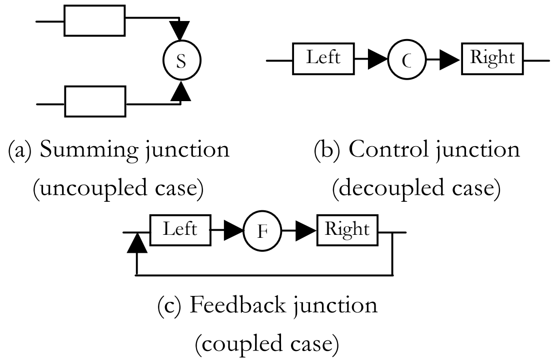


Figure 7. Representation of the design at each junction

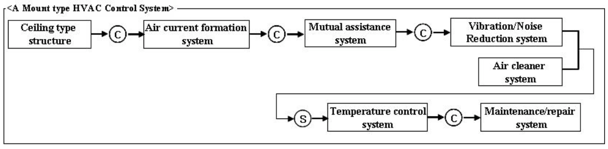


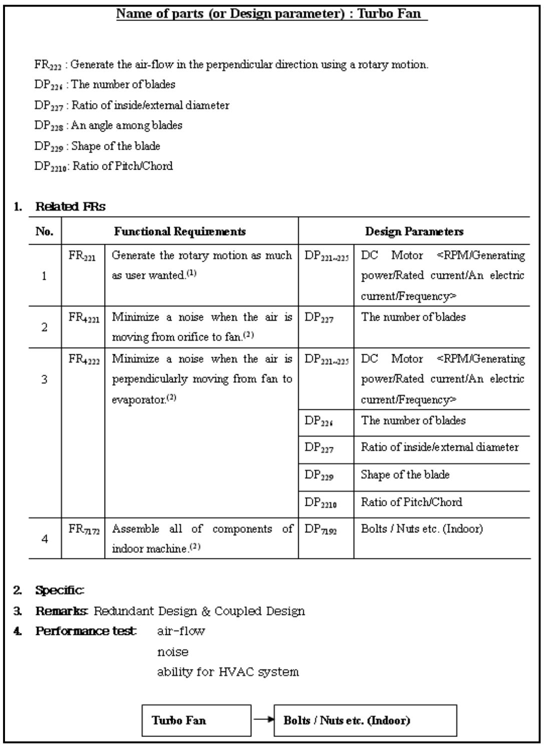
Figure 8. Design flow of a mount type HVAC control system

4.3 DESIGN MANUAL

The existing mount type HVAC control system has been designed with a somewhat regular standard, but it has defects to satisfy diverse demands. The entire design matrix and design flow give information to overcome the problems. However, it may not be easy for field designers to apply the improved design process which utilizes the axiomatic method since they are accustomed to the conventional way. A design manual is made to practically use the axiomatic design process.

An example of the design manual is shown in Figure 9. It consists of the name of the component which is familiar to conventional designers, design characteristics, relationships of the components and the related design flow.

In Figure 9, the name of Turbo Fan is a familiar word to conventional designers. DP_{226}–DP_{2210} are related DPs to the turbo fan and FR_{222} is a related FR. FR_{222} can be found when the diagonal elements for DP_{226}–DP_{2210} are X. The X terms in the columns of DP_{226}–DP_{2210} are found and the corresponding FRs are found, then they are related FRs in Figure 9. And the X terms in the row of FRs is found and they are related DPs. Therefore, related FRs and components for a certain component can be easily found. FRs, DPs, the characteristics and the flow are related to others by hyperlinks.



Name of parts (or Design parameter) : Turbo Fan

FR_{222} : Generate the air-flow in the perpendicular direction using a rotary motion.
DP_{226} : The number of blades
DP_{227} : Ratio of inside/external diameter
DP_{228} : An angle among blades
DP_{229} : Shape of the blade
DP_{2210}: Ratio of Pitch/Chord

1. **Related FRs**

No.	Functional Requirements		Design Parameters	
1	FR_{221}	Generate the rotary motion as much as user wanted.(1)	$DP_{221\sim225}$	DC Motor <RPM/Generating power/Rated current/An electric current/Frequency>
2	FR_{4221}	Minimize a noise when the air is moving from orifice to fan.(2)	DP_{227}	The number of blades
3	FR_{4222}	Minimize a noise when the air is perpendicularly moving from fan to evaporator.(2)	$DP_{221\sim225}$	DC Motor <RPM/Generating power/Rated current/An electric current/Frequency>
			DP_{226}	The number of blades
			DP_{227}	Ratio of inside/external diameter
			DP_{229}	Shape of the blade
			DP_{2210}	Ratio of Pitch/Chord
4	FR_{7172}	Assemble all of components of indoor machine.(2)	DP_{7192}	Bolts / Nuts etc. (Indoor)

2. **Specific:**
3. **Remarks:** Redundant Design & Coupled Design
4. **Performance test:** air-flow
   noise
   ability for HVAC system

Turbo Fan → **Bolts / Nuts etc. (Indoor)**

Figure 9. An example of the design manual

5 CONCLUSIONS

A rational and effective design process for a mount type HVAC control system is proposed by an axiomatic design process using the Independence Axiom. The hierarchy of the design is made by decomposition of FRs and DPs and the entire design matrix is made based on the hierarchy. The design flow is established from the design matrix and a design manual is made to exploit the new design process in practice.

We found some differences between the conventional design and improved design process using axiomatic design. The conventional way is mostly summation after designing modules and the design process generally links the modules sequentially. The improved design process is more effective for designers not only to understand the overall design process, but also to meet the diversity of demands for customers or designers for the mount type HVAC control system.

It is noted that there are coupled and redundant aspects for ability of air-cooling (air-flow, refrigeration cycle) and noise in the HVAC system. It is known that the design process is fairly inefficient and time-consuming because there are a lot of feedbacks. At this moment, coupled aspects are identified and design change is not carried out. Future research is needed to change the coupled parts.

6 ACKOWLEDGEMENTS

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