International Journal of Fuzzy Logic and Intelligent Systems, vol. 4, no. 1, June 2004 pp. 12-17

A Study on the Introduction of Fuzzy system into the Decision-Making process of HVAC designers

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Abstract

This study is designed to grope for logical methods in the decision-making process of human beings such as creation and analysis. With this in mind, the paper worked with a process where the designers of a design team gather and analyze their opinions in a design process to decide on the HVAC system of buildings. The paper introduced the fuzzy theory, or one of the methods to quantitatively describe language values with ambiguous features, suggesting a method to determine the judgement and suggestion values of the HVAC designers with the characteristics of language variables as the values of design factors greatly influencing the HVAC system. As a result, the paper tested the possibility of the fuzzy system as a logical method to gather the judgement of HVAC designers in a stage of HVAC type selection exerting a great influence on the experience and judgement of the designers and having powerful linguistic features and to determine an appropriate HVAC type which can satisfy the suggested values of related design factors.

Key Words : Fuzzy Logic System, HVAC type, Design Factors, Programming and Schematic design

1. Introduction

Creation, analysis and the like have been recognized as the unique sphere that belongs only to human being. In particular, in the sphere like architecture that combines mechanical and artistic aspects at the same time, our ability to create and analyze something has considerable impact on the resulting outcomes. However, in view of the analysis for the construction processes of new buildings, it is obvious that the expertise, know-how and intuition or the like of technical engineers in each field - architectural design, equipment, structure, execution, etc. - have significant influences on major decision-making processes for architectural design, which may determine the quality of architectural buildings as outcome. In this decision-making process for architectural design, while we combine and analyze the judgment of technical engineers for any appropriate design value of design factors, logical methodologies appear to be more necessary to enhance the quality of architectural buildings rather than those based on experiences or intuition.

Thus, this paper focuses on HVAC(Heating, Ventilation and Air Conditioning) design as one of architectural fields, and intends to suggest some logical methodologies for the process in which teamwork-based designers can combine or coordinate and analyze their respective opinions in the design process to determine HVAC type. For this sake, this study attempts to introduce so called 'fuzzy theory', a methodology to quantitatively describe linguistic values that often show ambiguous characteristics. Furthermore, it also suggests how to decide which judgment and proposed values of HVAC designers, which are characterized by linguistic variables, are available as the values of major design factors to determine HVAC type.

To meet these objectives, the basic procedures of this paper can be outlined as follows:

First, analyze the HVAC design process on the basis of questionnaire survey, interview, references and the like to set a decision-making process in HVAC design team and related design factors.

Secondly, analyze the possibility to introduce the fuzzy system for a set of decision-making process and design factors as mentioned above.

Thirdly, establish a basic structure for decision-making process among HVAC designers on the basis of the results analyzed in previous procedures.

Finally, perform a case study for the HVAC type selection of actual building in order to review any applicability to HVAC design process for basic decision-making structure as established.

2. Analysis of Decision-Making Process and Design Factors

2.1 Analysis of HVAC design and related decision making process

Similarly to architectural design, the HVAC design for architectural buildings refers to a process to judge and determine an appropriate value of numerous design factors interconnected with each other. These studies on design process have been performed by many researchers since the beginning of 1970's so as to objectify conventional design process in more formulated manner than before, which was largely dealt in customary and intuitive aspect for a long

Manuscrip received Apr. 13, 2004; revised Jun. 2, 2004.
이 논문은 한국과학재단의 해외 Post-doc. 연수지원에 의하여 연구된 결과의 일부임.

time[1]. To achieve desired goals, these studies have involved a variety of methods such as interview, participant observation, psychologic experiments and cognitive science. However, in order to establish a HVAC design process in a little more realistic and objective aspects, which comes to be a foundation for suggesting logical methodologies in decision-making process among HVAC designers, this study attempted to establish the process with reference to the results of interview with on-site HVAC designers, various literatures, my private judgment, etc. rather than existing diverse and complicated methodologies.

In general, HVAC design process can be subdivided into 4 steps such as Design programming, Schematic design, Master design, Execution design[2,3]. Design programming indicates a step for discussion with owner and architectural designers so as to extract design conditions like location, scale, usage and budget of a target building, and collect data about quality of HVAC, operational plan, potential expansion in near future, while setting the reasonable direction of design. Schematic design means a step to make a basic planning report and a rough construction budget on the basis of data and design direction as extracted in the step of design programming. Here, we have to examine architectural space, HVAC zoning, HVAC type, energy-saving measures and the like to decide how much the HVAC system level should be. Master design refers to a step for suggesting the basic planning report made at schematic design in a little further depth. Here, we have to estimate major equipments by load calculations with architectural plan and section determined, decide ducting and piping plan, and examine whether such design and plan may meet the conditions of whole budget. Finally, execution design refers to a step to make and embody something determined at previous steps into actual drawings. Here, we have to prepare various equipment drawings, specifications, calculational report and the like. Based on the results of interview, questionnaire survey and literature-based investigation herein, each step of this HVAC design process can be illustrated in detail as shown in Fig. 1.

But master design and execution design in HVAC design process indicate the steps depending on mathematical methodology, so they don't have very much effect on HVAC system in itself to be determined. On the other hand, in the step of design programming and schematic design, the HVAC type and level may be differently determined relying on the judgment of HVAC designers, applied data and so forth. In view of HVAC design process as shown in Fig. 1, the steps after load calculations in each room and zoning indicate the step of master design and execution design to be determined depending on mathematical methodology, while setting design conditions, and deciding HVAC zoning/type mean the step of design programming and schematic design that are likely affected by designer's judgment and data. In view of the process of combining and analyzing the opinions from HVAC designers in the step of design programming and schematic design, there is a series of courses such as data collection, combination, analysis and decision, in which a design team leader collects different opinions from design team members who are all qualified for HVAC design works, and then the appropriate values of design factors as applicable are determined after further discussion. Yet, this process also incorporates even illogical courses in which the experiences and intuitions of design team leader may have remarkable influences on the value to be determined.

Therefore, focusing on this step of design programming and schematic design, this paper aims to propose how to make logical decisions in the course of combining and judging the different opinions from HVAC designers.

2.2 Analysis of decision-making factors

To set design factors that need the experience and intuition of HVAC designers in design process, this paper attempted to investigate and analyze the related design factors in the step of design programming and schematic design as studied herein with regard to HVAC design process that is analyzed in previous section. The results could be outlined as shown in Table 1. Above all, the step of setting design conditions is to make basic design orientation for the ultimate purpose and goal of using a target building under designing, in order to perform a designing work. For the sake of this design orientation, it is demanding to identify and analyze the intention and character of owners or end users in advance, so that they may be reflected on the course of setting design conditions. Contrary to architectural designs, however, the conditions of HVAC design are mostly determined in the course of architectural design, so the conditions are less complicated than those of architectural design. Accordingly, the determinants of design conditions affecting the level and direction of this HVAC design can be outlined into two factors, i.e. building and weather. In the step of deciding HVAC zoning, when design conditions are set up, we have to choose certain HVAC type that may meet the design conditions. Before doing so, it is required to implement HVAC zoning that allows us to design several compartments for running HVAC system and control each system depending on the room conditions of installation. As a foundation for making decisions about HVAC type, the determinants of HVAC zoning can be categorized into room condition factors related to pollution, energy and indoor behaviors. After design conditions and HVAC zoning are determined, the step of setting HVAC type is to decide a HVAC type that may meet most design conditions and be suitable for zoning. In view of a general process of deciding HVAC type, two or three types are empirically nominated out of various types on the basis of previous performance and the like. Then the last one is finally selected from them by comparison and review. Here, the factors under such comparison and review are modeled on typical factors such as machinery installation space, equipment cost, operating cost and energy cost. Based on the results of survey and interview, however, this study investigated the determinants of HVAC type in a little further depth. As a result, we can divide them into general determinants and other determinants related to the functions of building.

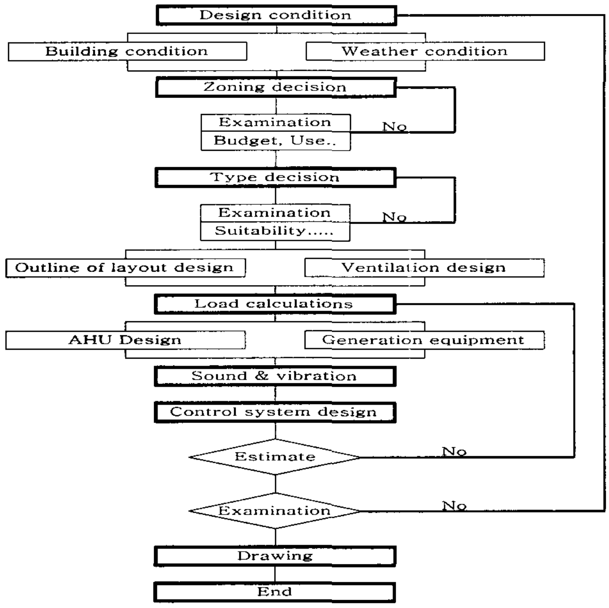

Fig. 1. Process of HVAC design

Table 1. Principal design factors for programming and schematic design

Phase	Conditions	Principal design factors
Design condition	building	Building use, Building scale
	Weather	Outdoor weather
Zoning decision	Indoor pollution	Ventilation number, Indoor atmospheric pressure, Air cleaning, Air filtering capacity
	Energy	Schedule, HVAC characteristics of major rooms
	Indoor behavior	Indoor temperature/humidity, Indoor environmental characteristics of major rooms
Type decision	General	Energy cost, Initial investment, Location of machinery under installation, Number of HVAC zones, Merit/demerit of each HVAC type, HVAC control system
	Function	Indoor pollution level, Operational method

These design factors have more or less ambiguous linguistic characteristics. Especially, out of these processes, the step of HVAC type, the first step of HVAC type decision at which the direction of HVAC system is decided, is the process to decide the suitable HVAC type which can be satistified with the proposal value best by HVAC designers' experience of the design factors related out of such HVAC types as All-air, Air-water and All-water. The logically suitable value is to be got by introducing the fuzzy logic system out of these steps, which is a kind of decision-making process. The result that the design factors related are investigated and arranged on the base of the questionnaire, interview and references, is like what is shown in Table 2.

Table 2. Design factors for decision of HVAC type

Design factors	Range of value
Economizer cycle	Very necessary ~ Very unnecessary
Humidity control	Very important ~ Very unimportant
Individual control	Very necessary ~ Very unnecessary
Indoor air quality	Very important ~ Very unimportant
Low noise	Very important ~ Very unimportant
Simultaneity (cooling & heating)	Very necessary ~ Very unnecessary
Architectural area	Very enough ~ Very unenough
· Mechinery area	Very enough ~ Very unenough
Expansion	Very important ~ Very unimportant
Waste heat recovery	Very necessary ~ Very unnecessary
Low initial investment	Very important ~ Very unimportant
Low maintenance cost	Very important ~ Very unimportant

3. Rule-Based and Establishment the basic structure of Decision-Making Process

3.1 Fuzzy system and decision-making process

In 1965, professor Zadeh introduced a new methodology called 'Fuzzy Set' to describe ambiguous linguistic values quantitatively[4]. Afterward, it has been further developed and applied across various fields. In particular, the FLSs (Fuzzy Logic System) based on fuzzy logic and rule is often used as a mean to express subjective knowledge and solve our daily problems in reality. As shown in Fig. 2, rule-based FLS is composed of four components such as rules, fuzzifier, inference engine and output processor. As a key role in rule-based FLS, rules(rule-based) are generated through HVAC designers' knowledge in practice and various data collected from existing works. Rules consist of If-Then structure. Input data and output results are available as linguistic variables like qualitative design factor for running system through fuzzifier and non-fuzzifier process.

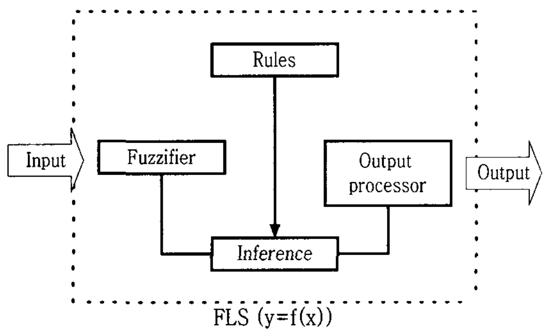

Fig. 2. Fuzzy Logic System

In the step of design programming and schematic design for HVAC design as analyzed in previous section, these FLSs may be useful as a decision-making method to determine the values of design factors related to the step of setting HVAC type, which has stronger linguistic characteristics than other steps. That is, most design factors itself are not unambiguously defined and most of corresponding solution methods are not determined, either. Besides, most of proposal values as suggested by HVAC designers in the step of design programming and schematic design are ambiguous and exist in the form of linguistic variables.

3.2 Setting basic structure of decision-making

As shown in the results of analysis as above, in view of decision-making process among HVAC designers such as data collection, combination/analysis and final determination, data collection indicates a step of collecting design data like opinions and experiences of HVAC design team members, internal/external design conditions, design data and literatures. Combination and analysis means a step of inference for deciding design values based on collected data. And final determination indicates a step of deciding appropriate design values in the end through the step of inference. In this course, the core portion comprises the step of combination and analysis to infer reasonable design values based on collected data. In this step, we can introduce the concept of Rule-Based FLS and organize basic structure of combination and analysis for making decisions as follows:

Step 1: Determine the value of linguistic variables.

Based on the concept of linguistic variables to express natural languages as introduced by professor Zadeh, the linguistic value of design factors and their membership functions were determined. As shown in Fig. 3, the values of basic linguistic variable for design factors and their membership functions were set as 5-step linguistic values and triangle functions.

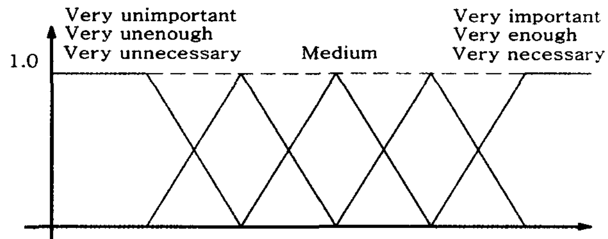

Fig. 3. Linguistic value

Step 2: Determination of Average Fuzzy Number

Based on experience, opinion and collected data or the like of each HVAC designer, we set design values for design factors, and then convert them into the fuzzy number. We can average the fuzzy number based on fuzzy numbers as converted for design factors. That is, the average of n fuzzy numbers for ith design factor can be calculated by Equation (1).

$$\widetilde{T}_{ij} = \sum_{j=1}^{n} (a_{ij}, b_{ij}, c_{ij}) / n = (\widetilde{a}_{ij}, \widetilde{b}_{ij}, \widetilde{c}_{ij}) \quad (1)$$

$\widetilde{T}_{ij}$: Average Fuzzy Number

Step 3: Non-fuzzifier for fuzzy number

Average fuzzy number can be converted into the value of linguistic variables by non-fuzzifier process. That is, it can be converted into Crisp Number by Equation (2)[5] and the degree of membership can be calculated by Equation (3)[6].

$$x_i = (\widetilde{a}_{ij} + 2\,\widetilde{b}_{ij} + \widetilde{c}_{ij})/4 \quad (2)$$

$$u_A(x_i) = \begin{cases} 0 & x_i < a \text{ or } x_i > c \\ (x_i - a)/(b-a) & a \le x_i \le b \\ (c - x_i)/(c-b) & b \le x_i \le c \end{cases} \quad (3)$$

x_i : Crisp Number

$u(x)$: Degree of Membership

Step 4: Inference of appropriate design values

Based on the membership function of linguistic variables and their degree of membership as calculated in each design factor, we can infer proper design values. Based of IF-THEN rules as ordered, we can make infer those values by introducing the course of inference as proposed by Mamdani[7] as shown in Fig. 4.

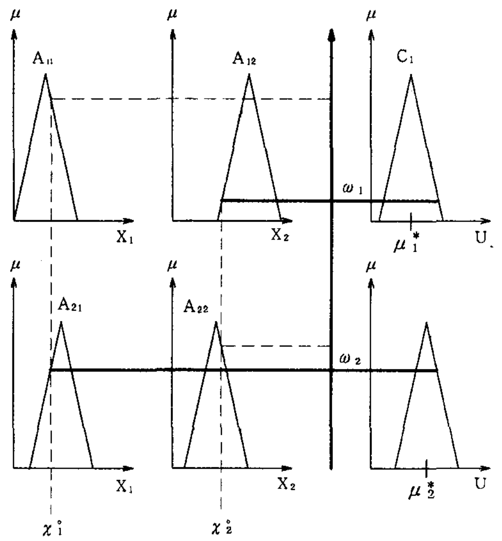

Fig. 4 Mamdani's inference process

3.3 Rule-based of design factors

Based on questionnaire survey, interview and references, the appropriate design values for required value of design factors as related to the step of setting HVAC type were collected and arranged in each HVAC type. As shown in Table 3, every rule base was built up by 60 rules. These rule bases become a basic data to determine an appropriate value for each design factor in decision-making process based on fuzzy system.

Table 3. Example of Rule-base with respect to design factors

Design factors	Qualities	All-Air	Air-Water	All-Water	Package Unit
Individual control	Very necessary	Poor	Poor	Good	Good
	Necessary	Poor	Suitable	Good	Good
	Medium	Poor	Good	Suitable	Suitable
	Unnecessary	Suitable	Good	Suitable	Poor
	Very unnecessary	Good	Good	Poor	Poor
Low noise	Very important	Good	Poor	Poor	Very poor
	Important	Good	Suitable	Very poor	Poor
	Medium	Good	Good	Suitable	Poor
	Unimportant	Suitable	Suitable	Suitable	Suitable
	Very unimportant	Very poor	Poor	Suitable	Very good
Architectural area	Very enough	Very good	Good	Suitable	Very poor
	Enough	Good	Very good	Suitable	Poor
	Medium	Suitable	Suitable	Good	Good
	Unenough	Poor	Poor	Suitable	Very good
	Very unenough	Very poor	Poor	Poor	Very good

Table 4. Proposal values of design team members

Design factors	Member 1	Member 2	Member 3	Member 4	Crisp number
Economizer cycle	Necessary	Medium	Necessary	Medium	3.5
Humidity control	Important	Medium	Medium	Important	3.5
Individual control	Very necessary	Very necessary	Necessary	Necessary	4.4
Indoor air quality	Medium	Important	Important	Important	3.8
Low noise	Important	Very important	Important	Very important	4.4
Simultaneity (cooling & heating)	Medium	Medium	Necessary	Necessary	3.5
Architectural area	Unenough	Unenough	Medium	Medium	2.5
Mechinery area	Medium	Medium	Unenough	Medium	2.8
Expansion	Medium	Medium	Important	Important	3.5
Waste heat recovery	Necessary	Necessary	Necessary	Medium	3.8
Low initial investment	Very important	Important	Very important	Important	4.4
Low maintenance cost	Very important	Very important	Important	Important	4.4

4. Case Study

4.1 Decision-making in HVAC design team

By means of an example, we can apply the results of studying logical decision-making methods by introducing fuzzy system into decision-making process of HVAC designers. That is, as analyzed in previous sections, we can apply the results to the decision-making process among HVAC designers in the step of setting HVAC type with design factors that show much ambiguous linguistic characteristics. For this sake, this study targeted an office building with one story below and ten above the ground(gross area : 4,560m2, architectural area : 556m2), which was supposed to be built in downtown of a metropolitan city. First, in the step of design programming and schematic design, we have to propose the values of design factors associated with the step of setting HVAC type in accordance with experience and judgment of HVAC design team members. Then, we can make decision to have one value by equation (1) and (2) based on the values as proposed. We can outline the results of this process as shown in Table 4. For instance, in view of the course for "individual control",

with regard to equation (1),

$$(4,\ 5,\ 5)+(4,\ 5,\ 5)+(3,\ 4,\ 5)+(3,\ 4,\ 5) = (3.5,\ 4.5,\ 5)$$

with regard to equation (2)

$$(3.5 + 2\times4.5 + 5)\ /\ 4 = 4.4.$$

Table 5. Defuzzifier of design factors

Design factors	Decision-making value	All-air	Air-water	All-water	Package unit
Economizer cycle	Medium (0.5), Necessary(0.5)	0.7	0.8	0.3	0.3
Humidity control	Medium (0.5), Important(0.5)	0.7	0.8	0.4	0.4
Individual control	Necessary(0.6), Very necessary(0.4)	0.3	0.42	0.82	0.78
Indoor air quality	Medium (0.2), Important(0.8)	0.7	0.86	0.34	0.3
Low noise	Important(0.6), Very important(0.4)	0.7	0.42	0.18	0.22
Simultaneity (cooling & heating)	Medium (0.5), Necessary(0.5)	0.7	0.6	0.5	0.5
Architectural area	Medium (0.5), Unenough(0.5)	0.4	0.4	0.6	0.7
Mechinery area	Medium (0.2), Unenough(0.8)	0.34	0.18	0.5	0.46
Expansion	Medium (0.5), Important(0.5)	0.3	0.3	0.9	0.7
Waste heat recovery	Medium (0.2), Necessary(0.8)	0.7	0.7	0.5	0.5
Low initial investment	Important(0.6), Very important(0.4)	0.22	0.18	0.74	0.7
Low maintenance cost	Important(0.6), Very important(0.4)	0.22	0.18	0.5	0.78

Table 6. Compatibility of HVAC type

Inference value	All-air	Air-water	All-water	Package unit
Compatibility	5.98	5.84	6.28	6.34

4.2 Determination of Suitable design value

Based on appropriate design values for design factors as determined by equation (3), we can infer a suitable

HVAC type. In view of this process, Here, Mamdani's inference process is applied to calculate an output value Bi' for an input value Ai' of design factor as set by HVAC design team. In this process, the linguistic value of inference value Ci' is used as defined in Fig. 4, and design values as inferred in each design factor are unfuzzified by 'Center of Gravity Method' as shown in equation (4). Based on the values calculated in each HVAC type by equation (5) from unfuzzified values in each design factor, we can decide the best suitable HVAC type.

$$u_i^* = \mathrm{COG}(C_i) \quad (4)$$

$$u^* = \sum_{i=1}^{12} u_i^* \quad (5)$$

u^* : Degree of Compatibility

In view of this course, by equation (4), in case of All-air,

(0.6×0.3 + 0.4×0.3) / (0.6+0.4) = 0.3

in case of Air-water,

(0.6×0.5 + 0.4×0.3) / (0.6+0.4) = 0.42

in case of All-water,

(0.6×0.9 + 0.4×0.7) / (0.6+0.4) = 0.82

in case of Package Unit,

(0.6×0.7 + 0.4×0.9) / (0.6+0.4) = 0.78

This inference was performed in each design factor as shown in Table 5, and whole design factors were inferred with equation (5). The results of analysis were obtained as shown in Table 6. Thus, it was found that the best appropriate HVAC type was "Package Unit".

5. Conclusion

Based on fuzzy system, this paper investigated decision-making process among HVAC designers for design factors in the step of setting HVAC type, which show strong ambiguity of linguistic variable in the step of design programming and schematic design. As a result, it was found that the decision-making structure among HVAC designers was similar to fuzzy logic system, so that proposed values of HVAC designers for design factors could be logically integrated in one value. Moreover, it was also found that such decision-making structure was available as a method to decide an appropriate design(i.e. the best suitable HVAC type as described herein) based on the integration of proposed value of each design factor. With regard to this decision-making method based on fuzzy system, it is necessary to follow up further studies so that such method can be applied to the step of setting HVAC system, and whole process of architectural HVAC design as well. Furthermore, it is prerequisite to make these theories as an application program so that they may be usefully applied into practical fields.

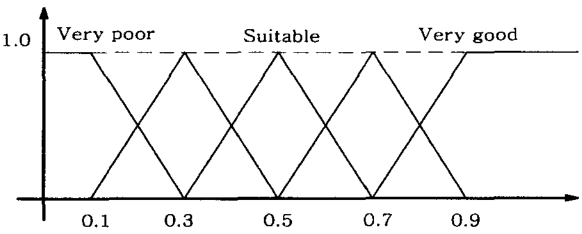

Fig. 6 Linguistic value

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