ICCEPM 2022
The 9th International Conference on Construction Engineering and Project Management
Jun. 20-23, 2022, Las Vegas, NV, USA

Identification of target subjects and their constraints for automated MEP routing in an AEC project

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Abstract: Since Mechanical, Electrical, and Plumbing(MEP) routing is a repetitive and experience-centered process that requires considerable time and human resources, if automated, design errors can be prevented and the previously required time and human resources can be reduced. Although research on automatic routing has been conducted in many industries, the MEP routing in AEC projects has yet to be identified due to the complexity of system configuration, distributed expertise, and various constraints. Therefore, the purpose of this study is to identify the target subjects for MEP routing automation and the constraints of each subject. The MEP design checklist provided by a CM company and existing literature review were conducted, and target subjects and constraints were identified through process observation and in-depth expert interviews for five days by visiting a MEP design company. The target subjects were largely divided into six categories: air conditioning plumbing, air conditioning duct, restroom sanitary plumbing, heating plumbing, and diagram. The findings from interviews show that work reduction and error reduction has the greatest effect on air conditioning plumbing while the level of difficulty is the highest in air conditioning duct and restroom sanitary plumbing. Major constraints for each subject include preventing cold drafts on air conditioning pipes, deviation in ventilation volume in air conditioning ducts, routing order on restroom sanitary plumbing, and separation distance from the wall on heating plumbing. In this way, subjects and constraints identified in this study can be used for MEP automatic routing.

Key words: MEP design, Design automation, Automation subjects, MEP routing constraints

1. INTRODUCTION

Mechanical, Electrical, and Plumbing (MEP) design identifies the location and route of building system components, which needs to avoid interference, comply with various design and operating standards, while also meeting building function and performance expectations such as comfort and stability [1]. MEP design has become more difficult with the increasing complexity and number of MEP systems in buildings in recent years while the MEP system space has become smaller. Accordingly, many experts in the construction industry agree, citing MEP design as one of the most difficult tasks in an Architect Engineering Construction (AEC) project [2]. Furthermore, the MEP part requires an accurate design because it has a relatively great impact on construction costs.

Nevertheless, reconstruction problems due to decreased accuracy and poor work often occur because most projects are conducted by manually expert experience, excessive costs and time are spent producing drawing, and human errors are made [3]. These problems occur because the MEP drawing and specification are delivered without proper inter-process clash check or cross-sectional review, which stems from the fact that the design period is short and the MEP drawing and specification are completed at the end of the design because the MEP design begins after the architectural design. If the MEP routing automation is realized, it will have a great effect such as preventing clash and design errors and drastically reducing the time and human resources required [4]. Recently, in many industries including aircraft, ships, and manufacturing, routing research that optimizes objective functions such as pipe length and bending through various algorithms has been being conducted [5-7], and studies are conducted for branch-pipe connections similar to architectural MEP routing [8-11].

Although MEP routing of AEC projects is similar to routing in other industries, it is considered one of the most difficult tasks of construction projects by many construction experts due to its complexity, distributed expertise and various constraints. Clear routing subjects and their constraints are not specifically defined because it is a repetitive and experience-centered process that requires considerable time and human resources. While the MEP routing process is repeated in all projects, there are few systematic methods to capture and store information generated in the process to formulate acquired knowledge and support future decision-making [1, 12].

In this paper, automated target subjects for the MEP routing are defined and the automation effect and difficulty of each subject were identified through a literature review, field visits, and expert interviews. Moreover, input information, constraints, and objective functions for the automation of the target subjects were identified.

2. METHOD

In this paper, three approaches were employed to define automation subjects and their constraints. First, the contents of the MEP design were apprehended through a CM company's MEP design checklist, and the components of the MEP automation were identified by reviewing existing studies [13-18]. Additionally, observation of work processes and expert interviews were conducted on the actual MEP design company for five days. Interviews were conducted with two people with more than 21 years of experience and one with more than 17 years of experience. For knowledge acquisition, since there is little information on MEP automation subjects and their constraints, data on MEP items were first collected through the MEP design checklist and drawing and specification review reports of the currently completed construction project. With existing studies on MEP design optimization and automatic routing, the knowledge required for key components of MEP was ascertained, and specific target subjects and their constraints have been defined through observation and interviews of experts working at project meetings [19].

Through the MEP design checklist, the process for reviewing the MEP drawing and specification, the outcome of the MEP design, was checked and the classification and contents of the MEP design were identified. The MEP drawing and specification review phase consisted of six categories: equipment installation work, air conditioning duct work, air conditioning plumbing work, sanitary pipe work, machine room work, and diagram. The appropriateness of MEP design was reviewed for each category based on laws, regulations, rules, and guidelines.

In existing studies, MEP routing or optimization was conducted through several constraints. For example, a study divided duct facility largely into air handling units (AHU), dampers, and ducts based on the MEP rule of the model checker to select free area and distance, property value, and existing equipment as important quality constraints [13], work minimized life cycle costs (LCC) by citing duct size and pressure balance as constraints [14], research sought for optimization by using the difference in ventilation volume and energy consumption in each room as constraints [15]. Other constraints were the water tank type, decompression valve method, zoning, and expansion joint of sanitary facilities [16], along with separation distance by pipe, multi-pipe creation, collision prevention, etc. [17, 18].

While staying at the MEP design company for five days observing the work of experts, practical constraints that had not been presented in the study were added and interviewed to obtain additional expert opinions. The main questions in the interview were as follows: i) are the target subjects and their constraints appropriate? ii) How effective is the automation for each target subject? iii) what is the difficulty level of automation by subject? iv) additionally, what are some considerations and constraints in the actual MEP design? Through these interviews, the subjects and their constraints were specified.

3. TARGET SUBJECTS FOR AUTOMATED MEP ROUTING

3.1. Identification of target subjects

Table 1. Target subjects for automated MEP

Category	Target subjects	Applies to
Air conditioning plumbing	indoor air conditioner arrangement	Non-residential
	automatic design of pipe routes	Non-residential
Air conditioning duct	automatic arrangement of ceiling supply and exhaust port	Both
	automatic design of duct routes	Non-residential
	automatic design of duct (ventilation unit) routes	Residential
Restroom Sanitary plumbing	automatic design of restroom sanitary plumbing	Both
Heating plumbing	automatic design of unit heating coil	Residential
Diagram	automatic drawing of diagram and flowchart	Residential

Based on the automation subjects classified by the MEP design checklist, the specific contents were identified by observing the work of experts and confirmed through interviews (Table 1). Subjects were largely divided into air conditioning plumbing, air conditioning ducts, Restroom sanitary plumbing, heating plumbing, and diagram, and their contents were classified according to the target building and components.

Air conditioning plumbing is mainly required in non-residential buildings, and automatic arrangement of indoor air conditioner is selected as an automated subject, and routing of air conditioning plumbing must be connected from vertical pipes to air conditioning devices. In this case, the air conditioner includes FCU, indoor unit, and EHP. It should be placed based on platting and load calculation data, and should be automated in consideration of the pipe diameter that changes according to the flow rate during routing.

The air conditioning duct selected the arrangement of supply and exhaust ports as one subject, which is needed for both non-residential and residential buildings. Routing of the air conditioning duct requires main duct routing and branch-duct routing that connects from the main duct to the air conditioner. The air conditioning duct of residential builidings consists of ventilation units, which are arranged in each household, and required to be routed to connect ventilation equipment that mainly placed in a utility room and each supply and exhaust ports. The supply and exhaust port should also be arranged based on the platting and load calculation data, and should be automated in consideration of the duct size that varies according to the flow rate during routing.

Restroom Sanitary plumbing includes various pipes such as water supply, hot-water supply, recirculation, sewage, drainage, and ventilation. In addition, sanitary equipment that needs to be connected to vertical pipes is mainly concentrated in the restroom. Thus, restroom sanitary plumbing is mentioned as the main automation subject. The routing of sanitary pipes must be connected from sanitary equipment to vertical pipes according to the arrangement of sanitary equipment. As per the above-mentioned pipes and ducts, this should be an automatic routing in consideration of the pipe diameter that varies depending on the flow rate.

Heating plumbing is a pipe mainly built in residential buildings other than special cases. Non-residential buildings with relatively little need for floor heating use equipment such as FCU and EHP, so air conditioning plumbing is constructed. The heating plumbing of the unit household should be connected from the hot-water distributor to the heating coils of each room. The coil of the heating plumbing uses the same pipe without changing the pipe diameter according to the flow rate.

A diagram is to draw a flow chart and each system of various pipes such as air conditioning, water supply, hot water supply, sewage, and local heating. It is not possible for non-residential buildings to simplify and generalize a diagram, so the target of automation is limited to residential buildings. It is also not the primary subject of automation because it is not used in 3D BIM.

3.2. Target subject automation effects and difficulty

Interviews were conducted on the effect of automation application and its difficulty of each automation subject previously classified (Table 2). The effect of automation application was expressed as a reduction rate of work and an error reduction rate through automation when making MEP design. Difficulty was evaluated in five degrees: very easy, easy, complex, somewhat complex, and very complex. Reduced work was calculated according to the proportion of each subject in the general facility drawing and specification, and reduced error was calculated according to how many errors occurred when reviewing based to the checklist after completion of the facility drawing and specification. This was done comprehensively considering the complexity and number of constraints to be understood when design the subject, the career of the practitioner doing the task, and the diversity of alternatives.

As for the degree of reduced work, the automatic design of air conditioning ducts marked the highest value: indoor air conditioner arrangement (10%), automatic design of air conditioning plumbing (75%), automatic arrangement of supply and exhaust port (15%), automatic design of air conditioning ducts (80%), automatic design of ventilation duct unit) (75%), automatic design of restroom sanitary plumbing (75%), automatic design of heating plumbing for unit household (10%), and automatic drawing of diagram (75%). This means that the portion of air conditioning ducts in MEP design is large and it spends most time on design. As for the degree of reduced error, the automatic design of air conditioning plumbing recorded the highest value: indoor air conditioner arrangement (30%), automatic design of air conditioning plumbing (75%), automatic arrangement of supply and exhaust port (30%), automatic design of air conditioning ducts (40%), automatic design of ventilation duct unit (30%), automatic design of restroom sanitary plumbing (25%), automatic design of heating plumbing for unit household (10%), and automatic drawing of diagram (50%). This indicates that design errors occur most commonly when design air conditioning plumbing in MEP design that is currently dependent on the experience of experts.

As for the difficulty, heating plumbing for unit households showed the easiest automation: indoor air conditioner arrangement (easy), automatic design of air conditioning plumbing (complex), automatic arrangement of supply and exhaust port (easy), automatic design of air conditioning ducts (very complex), automatic design of ventilation duct unit (normal), automatic design of restroom sanitary plumbing (very complex), automatic design of heating plumbing for unit household (very easy), and automatic drawing of diagram (easy). The heating plumbing for unit households has a constant pipe diameter, and unlike other pipes and ducts, has no change in level. A program is commercialized, in which heating plumbing is automatically created when designating room boundaries. However, it is limited to CAD, a 2D program, and does not support the connection to a living room that is not rectangular and hot water distributor. On the other hand, the automatic design of air conditioning ducts and automatic design of restroom sanitary plumbing showed "very complex" levels, indicating that the difficulty of automation was high. Since the air conditioning duct is placed in the facility space in the ceiling, other process instruments such as lights and sprinklers should be considered, and it occupies a considerable amount of space because the volume is larger than that of pipes. In addition, it is difficult to select the optimal route because various alternatives may present themselves. Although restroom sanitary plumbing does not come with various alternatives compared to air conditioning ducts, the difficulty of automation is high because it should select an optimal route by adjusting the level so that pipes do not crash into one another, which is caused by putting many pipes in a small space, including water supply, hot water supply, recirculation, sewage, drainage, and ventilation.

Table 2. Target subject automation effects and difficulty

Target subjects	**Application effect of automation**		**Difficulty**
	Reduced work	**Reduced error**	
Indoor air conditioner arrangement	-10%	-30%	Easy
Automatic design of air conditioning plumbing	-75%	-75%	Complex
Arrangement of supply and exhaust port	-15%	-30%	Easy
Automatic design of air conditioning ducts	-80%	40%	Very Complex
Automatic design of duct(ventilation unit)	-75%	-30%	Normal
Automatic design of restroom sanitary plumbing	-75%	-25%	Very Complex
Automatic design of Heating plumbing	-10%	-10%	Very Easy
Automatic drawing of diagram and flowchart	-75%	-50%	Easy

4. CONSTRAINTS FOR AUTOMATED MEP ROUTING

In order to automate MEP routing, an input value for creating an environment must exist, and when automated, the final output value must be checked. In addition, optimal routing should be performed by complying with constraints and minimizing/maximizing the objective function based on input values. To this end, input values, output values, constraints, and objective functions for air conditioning plumbing, air conditioning ducts, restroom sanitary equipment, and heating plumbing routing were investigated [20]. At this time, the air conditioner arrangement and arrangement of supply and exhaust port were included in the constraints of air conditioning plumbing routing and air conditioning duct routing respectively. The automatic design of ducts (ventilation units) was included in the air conditioning duct routing because it is a part of the air conditioning ducts routing in residential buildings. Thus, more general considerations were identified as constraints for automation. Moreover, it is limited to 2D and the diagram was excluded because it is very difficult to be generalized and simplified.

4.1. Air conditioning plumbing

The input information, required to automatically route air conditioning plumbing to control temperature, humidity, and air quality, has cooling and heating load according to design criteria, cooling and heating methods of major rooms considering load generation patterns, zoning plans according to use time, and pipe diameter calculation methods. The output information has the arrangement of the indoor air conditioner and the route of the air conditioning plumbing. Constraints include the close arrangement of windows of indoor air conditioners to prevent cold drafts, the separation distance between indoor air conditioners, the restricted length of pipes, securing internal dimensions between outer walls and beams, and equal distribution of flow rates by zoning area. The objective function has the optimization of pipe diameter, number of bendings, pipe length, and energy consumption.

4.2. Air conditioning duct

The contents of the air conditioning duct are similar to those of the air conditioning plumbing because the roles are similar. Thus, air conditioning plumbing and air conditioning ducts are often used simultaneously. In this case, input information needs the load distribution plan of the two systems. The input information of the air conditioning duct includes the air conditioning method for major rooms, zoning plan, duct dimension design method, main duct arrangement method, duct route level, and size of connection between supply and exhaust port and air conditioning method in consideration of cooling and heating load and load generation pattern. The output information includes the arrangement, format, and size of the supply and exhaust port, and the aspect ratio of the main duct and branch-duct, routing of the main duct, branching point and routing of the branch-duct. Constraints include the location of the light and sprinkler, ventilation criteria, ventilation amount deviation limitation, aspect ratio limitation, duct expansion and reduction angle limitation, and separation distance between the supply and exhaust ports. The objective function has an operating area according to the optimal size for each duct, number of bendings, duct length, energy consumption, and fan performance.

4.3. Restroom sanitary plumbing

The input information of restroom sanitary plumbing requires the location of the sanitary equipment and the location of vertical pipes. Since it needs the information for each pipe, it basically requires the location of vertical pipes for water supply, hot water supply, recirculation, ventilation, sewage, and drainage. The output information is the route from the vertical pipe to each sanitary device. The constraints include the routing order of each pipe, punchable wall, and priority when the route for each pipe intersects. The objective function includes the pipe diameter, the number of bendings, the length of the pipe, and the appropriate level for each pipe.

4.4. Heating plumbing

Heating plumbing is mainly a method of placing coils on the floor in residential buildings, except in special cases. Input information on heating plumbing includes the heating methods which are divided into local heating, central heating, and individual heating, the location of vertical pipes, and the location of hot water distributors. In addition, distance between coils and total length of coil should be identified in advance because each constructor usually demands a different value.

The output information includes the heating coil arrangement of each room, the heating coil arrangement of the living room, and the connection with the hot water distributor. The constraints include the separation distance from the wall, heat insulation for about 1m initial entrance, and the shape of the coil. The objective function includes coil length, energy consumption, and deviation of each room.

5. CONCLUSION AND DISCUSSION

The MEP routing is a repetitive and experience-centered process that requires considerable time and human resources. Thus, if MEP routing is automated, it will be very effective in preventing interference or design errors and drastically reduce the required time and human resources [4]. However, there are few methods to systematically store process-generated information to formulate knowledge for MEP routing and support future decision-making [1]. Therefore, this paper defines the target subjects for the MEP routing automation and identifies automation effects, difficulty and input information, output information, and objective functions for each subject through literature review, observing process by visiting MEP design sites, and interviews with experts. MEP routing automation subjects are largely air conditioning plumbing, air conditioning ducts, restroom sanitary plumbing, heating plumbing, and diagram. The air conditioning plumbing marked the highest value in terms of the automation effect represented by the rates of the reduced work and the reduced error. For the difficulty of automation, air conditioning ducts and restroom sanitary plumbing showed the highest level of difficulty with “very complex,” whereas heating plumbing marked the lowest level of difficulty with “very easy.” There were similarities and differences of each subject in the input information, output information, constraints, and objective functions for automation. For example, air conditioning plumbing and air conditioning ducts showed similarity in input information, while air conditioning plumbing and restroom sanitary plumbing showed similarity in output information. However, the constraints had characteristic matters for each subject.
As a result of observing the process in the field to investigate considerations for the MEP routing automation, there were also a number of constraints that could be adjusted within a range other than strict constraints such as laws and design standards. In addition, as mentioned in Introduction, there are many matters that are determined at the discretion of experts. Therefore, it is expected that more diverse subjects can be extracted if future studies investigate considerations with a focus on soft constraints and expert decision-making. It is expected that subjects and constraints identified in such studies can be used to implement them as objective function formulas, and optimize and automate routing through future studies.

ACKNOWLEGEMENTS

This work is supported by the Korea Agency for Infrastructure Technology Advancement(KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant 22AATD-C163269-02).

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