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THE APPLICATION OF MEP SYSTEMS INSTALLATION FOR INTERFACE INTEGRATION IN BUILDING CONSTRUCTION

Sy-Jye Guo, Chi-Su Tai, and Hsiao-Ching Chen

Key words: MEP systems, construction management, interface integration, working sequences.

ABSTRACT

The mechanical/electrical/plumbing (MEP) systems employed in architectural engineering are complex and diverse. Improper integration at the equipment/pipeline interface results in interference and inappropriate sequence of jobs during installation can negatively influence the entire project. This study proposes useful guidelines and processes to avoid making mistakes in the integration of the interface, which would necessitate redoing work, increase costs, and delay completion. Eight criteria and three-level integration sequencing logic were adopted as the foundation for guidelines in the integration process. An eight-story laboratory with a total floor area of 20,000 m^2 was selected to verify the proposed guidelines and processes. The practicality of this system was verified through the elimination of fifteen major conflicts of equipment/pipeline arrangement following the application of these guidelines.

I. INTRODUCTION

Mechanical/Electrical/Plumbing (MEP) is the core segment of the architectural engineering industry, similar to the blood, nerves, and digestive system of the human body. These core tasks play the most critical role in the entire architecture/construction business, by providing a comfortable, safe living environment. MEP systems comprise multiple working categories and activities that sustain numerous complex arrangements of pipes throughout the entire industrial unit. Problems are frequently encountered when interfaces are improperly integrated, resulting in delays in the project and reduced product quality.

The major MEP installation interface integration (MEP III) projects require the identification of separate arrangements for HVAC (Heating, Ventilation and Air Conditioning), power supply, plumbing, fire protection, telecommunications, and other related systems. Hence, the purpose of integrating the interface is to recognize problems, resolve conflicts, and perfect the layout of the system for these mechanisms to serve their functions fully.

We conducted interviews with experts, field investigations, and a review of research papers. This study combined construction management elements, gathered pertinent knowledge, and analyzed the available information to attain: interface integration principles, solutions to interface conflicts, and a logical work sequence. Moreover, the complete integration of the interface reduces the numbers of changes in the design, decreases the work requiring demolition, addresses problems resulting from installation error, and increases the overall construction quality of projects.

II. RESEARCH BACKGROUND

Architectural engineering is a traditional industry, involving the creation of unique products. Currently, according to technical specifications, each specialty or trade subcontractor is assigned the responsibility of integrating MEP systems. Specialty subcontractors for each system should have sufficient construction knowledge required for the integration of MEP. The knowledge required for MEP integration must be integrated because specialty subcontractors of each system perform tasks individually, proposing a layout according to their own needs, leading to the fragmentation of MEP [17]. MEP integration has been researched and many 3D and 4D modeling tools have been created. In reality however, contractors seldom implement these modeling tools in the integration of MEP due to high costs and limited time. Few contractors are willing to invest the money and labor required to create a MEP 3D model for a single facility. In addition, most engineers are unfamiliar with these tools or the associated software applications. Engineers also have limited knowledge of the related input/output data and applicable model targets. Thus, the integration information of MEP

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system needs to be continually developed.

In recent years, research into MEP integration has focused mainly on generating 3D and 4D models and the related software applications used to implement system integration. Tatum and Korman [17] and Korman and Tatum [13] created a prototype computer tool for MEP coordination. Korman *et al*. [12] presented geometric and topological characteristics with which to define coordination information. Horman *et al*. [10] proposed a sequencing plan for electrical construction. Guo [8] established a strategy for identifying and resolving spatial conflicts in building construction. Pavitt and Gibb [16]. investigated interfaces within the management of construction focusing on building facades.

Anumba *et al*. [3] and Bouchlaghem *et al*. [4] created a visualization and communication environment to assist design teams in the communication of design details. Hartmann and Fischer [9] analyzed how 3D and 4D models support communications and scheduling. Mckinney and Fischer [15], Fischer *et al*. [6], and Anson *et al*. [2] discussed the application of 4D models in practical cases. Fard *et al*. [5] described the set of initial requirements for interactive workspaces to support the development and coordination of 3D design. Akinci *et al*. [1] formalized time-space conflict analysis as a classification task. Fischer *et al*. [7] developed virtual design and construction (VDC) technologies for coordinating MEP systems in a large healthcare project; however, this article failed to detail their working sequence arrangements or planning methodologies. Khanzode and Staub-French [11] provided guidelines to help project teams implement 3D and 4D modeling in building construction projects.

As previously mentioned, although 3D and 4D software can facilitate the integration of interfaces and escalate the construction process, this software cannot resolve all of the problems in a multi-disciplinary and multi-organizational environment [11]. The products of architecture are unique and non-repetitive, and MEP projects are varied and complicated. This makes it is impossible to clearly distinguish the boundaries between structures, between the structure and the MEP job, and between MEP systems.

Previous researchers failed to address the identification of conflict and the decision-making processes of experts. Moreover, they did not discuss the standards of expert judgments and provided no explanation of the software development process. Therefore, this study endeavors to:

(1) Define the components of the MEP system and analyze the characteristics of MEP interface problems to establish the guidelines for interface integration.
(2) Analyze categories of conflict in the MEP to create a mechanism for solving interface interferences.
(3) Verify the steps of MEP integration using an actual project to demonstrate how to apply integration principles to resolve interface conflicts and how to design working sequences as a whole to achieve the final goal of integrating MEP interfaces.

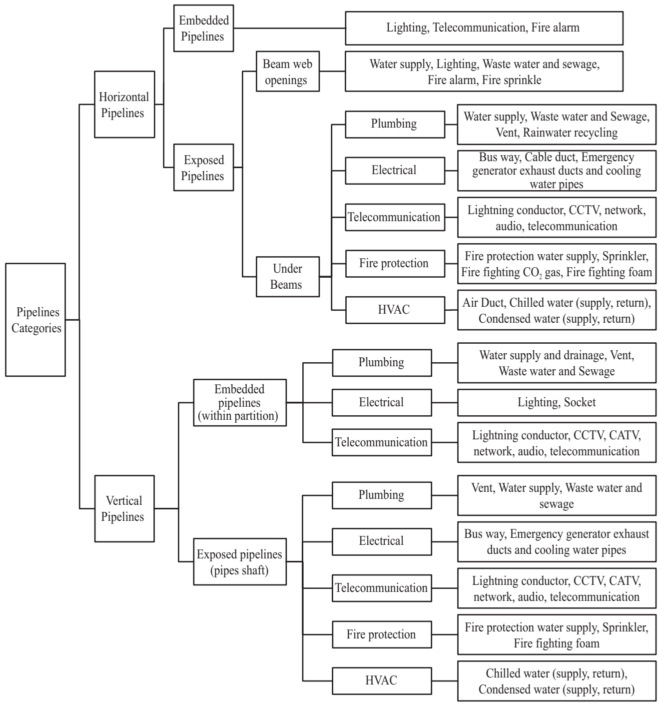


Fig. 1. Piping layout categories of MEP systems.

III. MEP III ANALYSIS

1. Interface Components of MEP Systems

This study classifies all of the equipment and pipelines (E&P) in a building according to types of component in the interface before analyzing MEP III. Based on the position of the MEP interfacial components, the E&P can be classified as the supply side, transmission side and terminal side [14]. The supply side produces and exchanges energy, using devices such as chillers and emergency generators. The transmission side, such as bus ways and electrical pipelines, transfers the energy from the supply side to the terminal side. The terminal side includes the equipment at the end of MEP system, such as lighting fixtures and air conditioner outlets.

Any two among the three interfaces—supply, transmission and terminal sides—are prone to various difficulties associated with the interface. Problems on the supply side and the terminal side do not include routing considerations making them more straightforward. More complex problems normally occur with the positioning of equipment in installation spaces and work around procedures. However, problems on the transmission side are more complicated because they involve the layout of wires and pipes (see Fig. 1). This study focuses on the interfacial interference on the transmission side, provided the relative importance of the problems and the nature of the integration solutions in MEP systems.

2. Eight Criteria and Three-Level Integration Sequencing Logic of MEP III

As indicated previously, experienced engineers are required to perform tasks associated with MEP integration; however, currently available research makes no mention of the identification of conflict or the decision-making process of managers, to provide logical principles on which to base MEP integration. For this reason, we assembled a team organized by three experienced MEP senior engineers and four experienced project managers. Team members identified major integration elements from the existing research papers such as constructability [16], maintenance [12, 17], and cost [10], discuss and study them repeatedly, and addressed the above mentioned problems according to the characteristics of the problem, integration requirements, and construction necessities. In this manner, we developed the following eight classification criteria of interface problems:

(1) "Coordination with civil structure works" refers to the process of installing E&P, which must be well coordinated to embed the horizontal pipes and vertical sleeves in advance. Electrical pipes, monitor control pipes, and vertical sleeves of sewage pipes from the floor slab must be installed prior to slab grouting. The work involving the first completed concrete mat for moisture protecttion, and vibration isolators must be executed in conjuction with the embedded sleeves and architectural construction works [10].

(2) "Safety" refers to safety considerations during installation. For example, safety is required to prevent hazards such as a water pipe leakage if a water pipe lies above an electrical pipe.

(3) "Functionality" refers to ensuring that the function of pipes is fully exploited while complying with building codes. For example, drainage slopes and routes must be taken into consideration for proper drainage of waste water. The installation of fire protection equipment and piping must be arranged prior to other systems in order for the entire fire protection system to comply with fire codes and fire protection permit drawings. Consequently, this has an impact on passing the fire protecttion inspection and obtaining the occupancy permits.

(4) "Constructability" [16] represents the factors influencing the sequence of installation. The conflicts can be categorized as follows:

- Conflict of equipment in a space: Because of the crowded space, the routing and sequence of installation for large equipment must be checked first.
- Conflict of pipeline in a space: Conditions for stacking and interlacing pipelines causes difficulty in installation and maintenance due to over-crowded spaces and lack of advance coordination.
- Crowded installation: Conflicts within the installation space, idle laborers, and poor installation quality can result from problems such as crowded spaces [8], or multiple workers operating simultaneously at a single site. Furthermore, the attitude of "first come first win" or "first do first win" causes conflict in the arrangement of pipelines.
- Pipe materials and dimensions: Installation suffers if the diameter of the pipe is oversized or if the material of the pipe is inflexible or too rigid to be easily cut or molded. If these kinds of materials are applied for the works, they should be installed earlier to prevent conflicts.
- Installation of pipeline tiers: When the pipeline layout exceeds two layers, pipes on the upper layer should be installed first.

(5) "Economy" refers to the cost estimates associated with integration, which can increase due to a lack of coordination. For instance, re-routing a pipeline increases the lengths of the pipeline and associated costs.

(6) "Efficiency" refers to a lack of integration causing descending pressure and consuming capacity, which influences the basic function of MEP systems. Additionally, venting conditions around equipment influences equipment functionality, and should be noted during the integration of the interface.

(7) "Expandability" refers to the lifecycle of the facility causing a demand for the expansion of pipelines due to the changes in usage or upgrades to the facility. This increasing demand requires consideration prior to the installation phase to ensure space for future expansion of the pipeline.

(8) "Maintainability" refers to the convenience of maintenance during the operation phase when arranging the pipeline. Maintenance space and operation route must be taken into consideration.

The above eight criteria were adopted as MEP integration items because they are closely related to considerations of installation integration. We called these eight criteria MEP III criteria. To facilitate comparison, this study subcategorized these eight criteria according to three levels of construction management based on architectural and MEP characteristics. The three levels are described as follows:

First, "Basic requirements and coordination with civil structure works" is the most important level that must be taken into consideration. "Basic requirements" means that integration works must satisfy the demands of function, regulations, and safety. Meeting regulations and safety requirements is the most important task in the design of a MEP system. Determining whether the system is effective and matches the design requirements is important during construction. "Coordination with civil structure works" means that pipes beneath concrete structures must be integrated in advance to facilitate concrete grouting schedules. Thus, the first mission of the MEP installation is to achieve the "Basic requirements and coordination with civil structural works." "Coordination with civil structural works," "Safety" and the

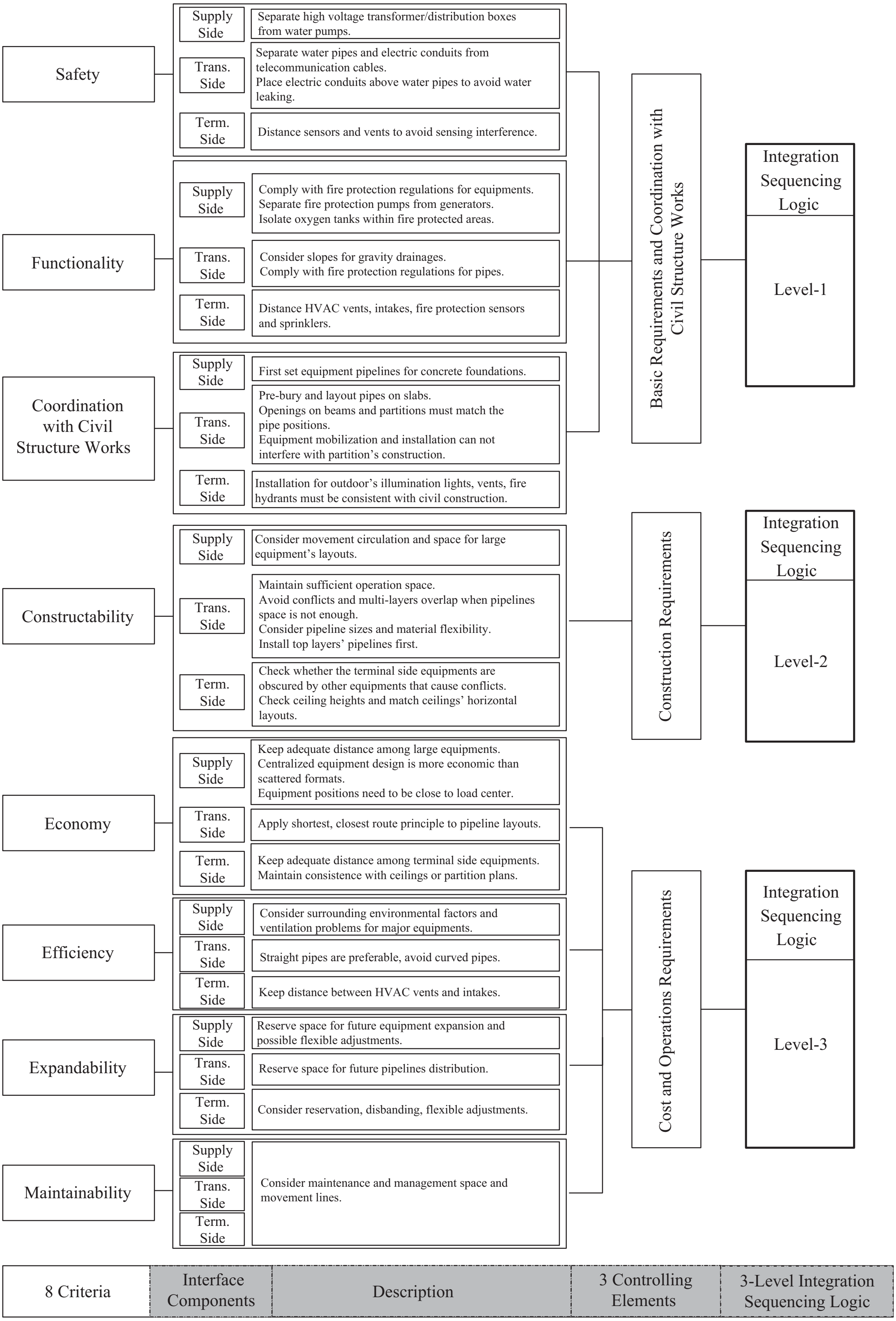


Fig. 2. Relationship between 8 criteria of construction interface integration for MEP systems and 3-Level integration sequencing logic.

"Functionality" of the 8 criteria fall under this first level of the integration sequencing.

Second, "Construction requirements" is a second level integration task, comprising the evaluation of installation difficulty, problems associated with the installation of circulation interfaces, and the arrangement of sequencing. The major integration task involves interfacial conflicts and working sequences between MEP and MEP systems, because the conflicts from both aforementioned situations have a considerable influence on the planning, sequence, and progress of construction. "Constructability" is a second level requirement related to the sequencing of integration.

Finally, "Cost and operations requirements" refers to the examination of the price of installation, cost-benefit ratio, and factors related to maintenance and expansion during the life circle of the facility. Integration at this stage must take into account whether E&P are cost effective, whether space is reserved for future expansion, and whether it provides easy maintenance. "Economy," "efficiency," "expandability," and the "maintainability" of the eight criteria fall under the third level requirement of the integration sequencing logic.

The established integration sequencing logic based on the three levels of construction management is called the "eight criteria and three–level integration sequencing logic," as shown in Fig. 2. This demonstrates the relationships among these levels and the eight criteria. It also provides examples illustrating the content of integration for the three interfacial components. In conclusion, the eight criteria are items that must be evaluated during the integration of MEP. The "three–level integration sequencing logic" is the foundation for resolving interface conflicts during integration.

IV. GUIDELINES OF MEP III

Each MEP system in a building is designed separately. This study addresses the integration processes for five MEP systems. Primary contractors normally integrate and overlay systems at the time of construction. Combined service drawing work (CSDW), also known as sequential composite overlay process [17], is the first step in MEP III, a discernible process in solving interface conflicts. CSDW requires a sequential overlap of one drawing over another, layer by layer. By utilizing this technique, experts can identify conflicts in E&P, and discuss solutions during routine meetings [7, 11].

In reality, the professional knowledge of experts is often transferred to novice engineers only varbally, without the advantage of documented records. Thus, this study collected the knowledge of experts and organized it logically to develop the principles for MEP III. We expected that these findings could be widely used by engineering personnel at each level. The intent was to improve the capabilities of all subcontractors, in establishing a common understanding during coordination to reduce disputes, and provide a clear logical means to create working sequences and progress networks.

1. IIDMS—Interface Interference Decision-Making System

CSDW is a necessary step in solving interfacial conflicts. A complete set of CSDW can resolve nearly any interfacial problem and provide appropriate working sequences for every subsequent job. Nonetheless, during the CSDW process, it is not unusual to encounter conflicts associated with the equipment and pipeline, requiring an immediate solution. By applying efficient interface integration principles, the above conflicts can be disentangled enabling the full function of the MEP system. A system that can identify, recognize, and resolve any type of interfacial conflicts is required; therefore, in this research we developed an IIDMS model based on MEP III principles (see Fig. 3).

During CSDW, all pipelines and equipment of MEP systems are lain together. Detection systems are applied to detect conflicts in the 2D plan. Two types of interfacial interference are common between the equipment and pipelines: overlap and cross. These are defined as "2D overlap" and "2D crossing." The detection system provides an alert in the case of interference detection.

In the IIDMS identification system, the "eight criteria and three-level integration sequencing logic" is employed to assess interfacial conflicts and determine guidelines for pipeline placement on either the upper or lower layer. According to the order of judgement from the first level to the third level, this system also identifies divergence, and determines whether the two layers that are overlaid or crossed are satisfactory.

Examples describing pipeline positioning principles during the first level of the three-level integration sequencing logic are presented as follows:

(1) Electrical pipes and telecommunication pipes should be installed above water pipes.
(2) Because the position of drainage pipes is related to drainage slope, they must be reviewed first while combining drawings. This is a primary activity to ensure the efficiency of water drainage.
(3) The fire protection system is regulated by fire regulations and permit drawings: thus, the fire protection system should be constructed first to ensure the architecture construction drawings are in compliance.
(4) Embedded pipelines within the floor and sleeves should be completed prior to grouting. The concrete mat and foundation for equipment also should be clearly illustrated in accordance with the construction drawings.

Based on the second level guidelines, the principles of piping are described as follows:

(1) In consideration of ease of construction and future maintenance, only two levels are allowed for the layout of pipelines.
(2) Pipes with an oversized diameter and hard material

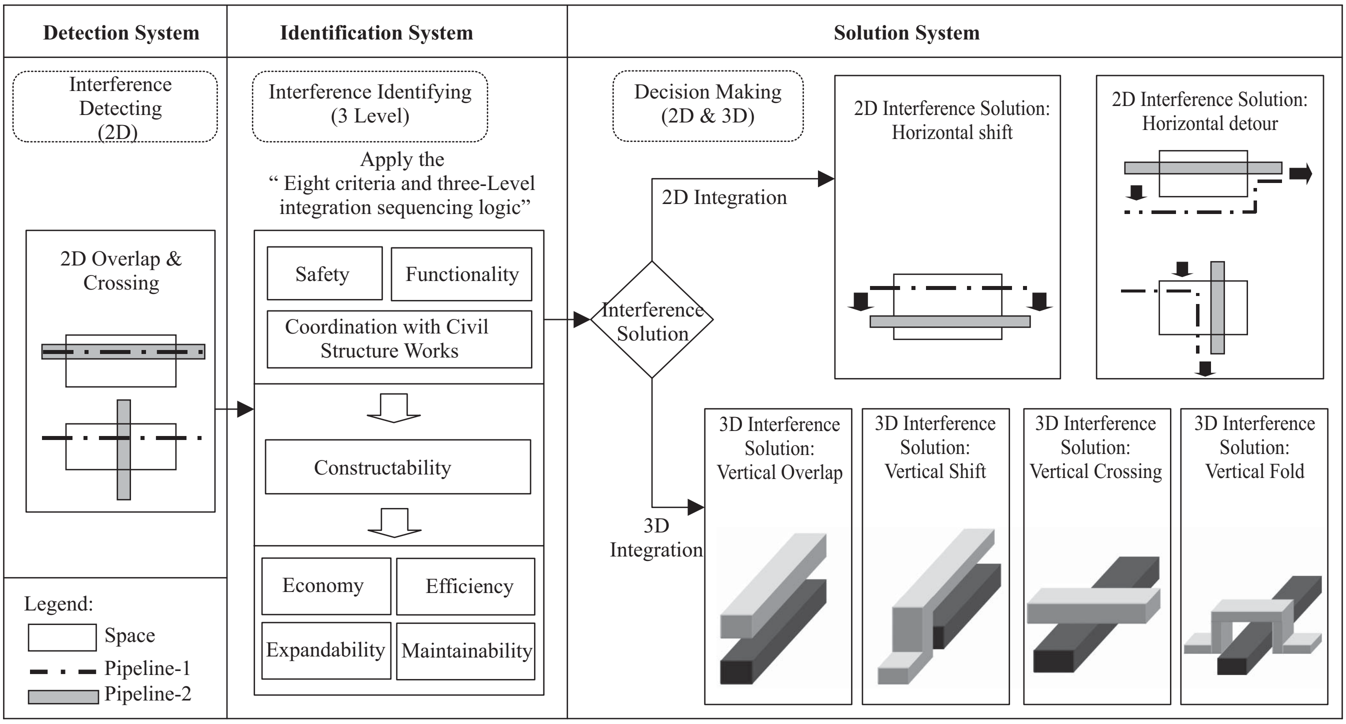


Fig. 3. Interface Interference Decision Making System (IIDMS).

should be placed at the uppermost level. HVAC ducts, smoke exhaust systems, and large main pipes in every system belong to this level.

(3) The routes and timing involved in moving large-scale equipment should consider movement circulation to avoid influencing equipment placement and future equipment mobilization.

Based on third level guidelines, the principles of piping are as follows:

(1) Piping should be laid out in a straight line covering the shortest possible distance to avoid bends and detours, and to conform to the principle of economy and energy benefit.
(2) The difficulty of future maintenance should be considered if pipelines are designed on more than two levels.
(3) Space for future expansion and maintenance should be reserved during the CSDW phase.
(4) For convenience of future investigation, moving and maintenance must be considered when deciding the location of equipment.

During the interactive comparison above, if it is determined that these two layers cannot be overlaid or crossed, we proceed to the "2D integration" step of the solution system. The solution system employs "2D interference solution: horizontal shift" or the "2D interference solution: horizontal detour" to deal with such conflicts. Alternatively, if overlaying or crossing on two layers is permissible, the solution system will use "3D integration" including: "3D interference solution: vertical overlap," "3D interference solution: vertical shift," "3D interference solution: vertical crossing," and "3D interference solution: vertical fold." The 3D integration model proposes conflict handling strategies, to determine the layout of pipeline elevations.

The "eight criteria and three-level integration sequenceing logic" is the core concept of IIDMS. This logic is responsible for identifying conflicts, assisting in the accuracy of judgments, and resolving confusion in the laying out of equipment/pipelines. By evaluating the three levels from the first level to the third level, this system provides a final decision based on the priority of the problems.

According to the IIDMS, the horizontal and vertical position of pipelines must be identified, adjusted, and integrated to prepare the appropriate 3D spacing and elevations prior to conducting designs in detail. Subsequently, the height of the ceiling and architectural structures also need to be revised to ensure structural safety in accordance with design criteria. As MEP integration work comes to an end, the E&P plans, profiles, cross sections, structure openings and 3D perspectives are completed. Reasonable job sequences are determined and the interfacial problems of subcontractors are coordinated and resolved according to adjusted pipeline elevations and the position of equipment. The intent is to reduce the number of errors associated with the installation of MEP and increase the performance and quality of the entire project.

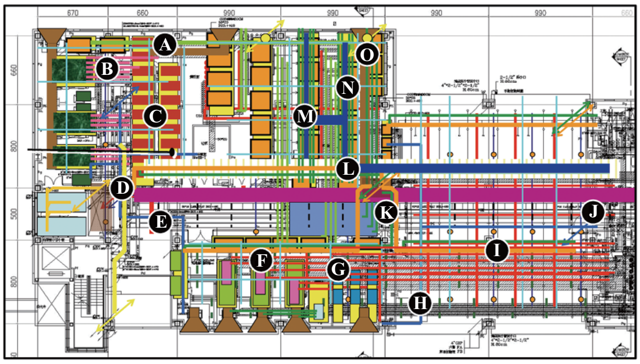


Fig. 4. Locations of interface interference.

V. VALIDATION FOR MEP III

1. Case Background

This research selected the mechanical room of a high-tech laboratory building to verify the proposed guidelines and processes. The laboratory is an eight-story structure with a total floor area of 20,000 m^2. The mechanical room is located on the left side of the first floor. The right side is occupied by offices and a hallway leading to all utility conduits between the mechanical room and the offices.

Five MEP systems were integrated within the building: electrical power, plumbing, HVAC, telecommunications, and the fire protection. The mechanical room comprised a transformer room, an emergency generator room, a UPS room, a Chiller room, and a gas room for cylinders.

2. Interfacial Interference before Applying the Integration Model

According to the rules and conventions of typical jobsites, specialist contractors propose construction plans and shop drawings individual scope prior to construction. The general contractor coordinates these construction plans and drawings in the CIP meetings (coordinate installation program) and organizes the entire installation program. In this case, the general contractor overlapped all of the MEP plans of the CSDW drawings. E&P were placed according to the original individual drawings. Five major systems and over a dozen kinds E&P were overlain in separate layers. The CSDW drawings became very complicated, and the conflicts among the different systems were obvious. Resolving the interference of these conflicts became divergent using multiple opinions. Furthermore, on-site engineers executed decisions according to the personal experience, making installation interference difficult to coordinate.

After numerous CIP meetings, fifteen major interference locations on the 2D plan remained unresolved (from circle A to circle O in Fig. 4). If these problems were not coordinated, disordered sequencing, delays, and insufficient work space would increase losses considerably.

3. Interface Integration after Applying Integration Model

To resolve these interference problems mentioned above, the research applied the IIDMS integration model and established the "Interface Integration Validation Table (IIVT)" as a validation tool to characterize the integration process. This table lists the location of interfaces, issues related to interfaces, the IIDMS model, and the sequence of installation. IIDMS is employed to resolve interfacial conflicts and determine whether pipelines could be overlaid and identify which pipes should be placed in the upper layer. The detection system, identification system and solution system are used to demonstrate the integration process.

The detection system illustrates the location of conflicts on the plan. Applying the "eight criteria and three-level integration sequencing logic," the identification system is used to evaluate the integration of the problems from the first to the third level. The solution system presents the final implementation of the integration. The integrated 2D plan, the cross section, and the 3D perspective diagram display the final integration. Finally, the sequence of the installation indicates the activities step by step, according to the elevation of E&P. Upper pipelines should be installed first, and lower pipelines installed last.

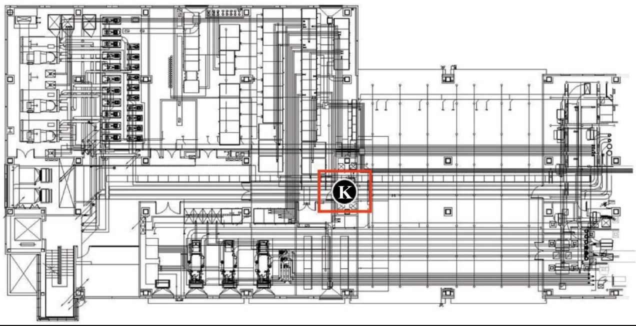
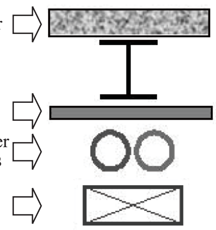
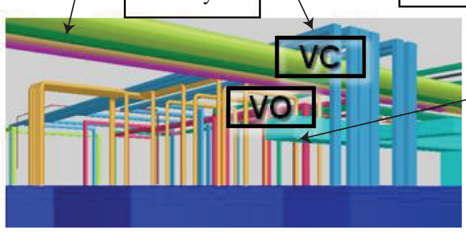
Table 1 verifies the integration of the interface in location K. The issue was associated with "interference between bus ways, chilled & condensed water pipes, and air ducts." The CSDW drawing displays the "2D overlap & crossing" situation and the Detection system then indicates the conflict location on the 2D plan. The identification system checks each eight criteria by item, from the first level to the third level.

In consideration of safety, the bus way should be located above water pipes (chilled/condensed water pipes). With regard to functionality, the building and fire protection codes were not an issue in this case. The air duct was larger than the other pipes; therefore, it should be placed in the upper layer; however, if the water pipes were placed from the corridor to the right hallway, it would be difficult to bend them. As a result, to maintain a higher ceiling height and a shorter the air duct, the air duct is placed in the lowest level. Third, the three kinds of pipes did not need to comply with civil structures in this location. Fourth, in consideration of constructability, the bus way should be installed before the water pipes, and the short air duct was installed last. Fifth, in consideration of budgetary issues, the number of bends in the water pipes was reduced. Sixth, in consideration of efficiency, placing the air duct on the lowest level reduced the number of detours required for the water pipes and improved the efficiency of the water pipes. Seventh, in consideration of expandability, most of the pipelines were located within two layers, which provided room for expansion. Finally, after revising the plan, maintenance was not an issue.

VI. CONCLUSION

MEP is an engineering task comprising multiple systems,

Table 1. Interface Integration Validation Table (IIVT).

Room/Location		Mechanical Room/Location K							
Interface Issue		Interference between bus ways, chilled & condensed water pipes and air duct.							
IIDMS	**Detection**	2D Overlap & Crossing 							
	Identification	**3-Level integration sequencing logic**							
		Level-1			**Level-2**	**Level-3**			
		Safety	Functionality	Coordination with Civil Structure Works	Constructability	Economy	Efficiency	Expandability	Maintainability
		bus way should be located above water pipes.	consider the higher ceiling height and the air duct is short, the air duct was placed on the lowest level.	no need to comply with civil structures in this location.	upper level is bus way which should be installed first. The middle level is chilled/condensed water pipes. The lower level is air duct which is short.	reduce the bending water pipes.	reduce the detour water pipes.	the majority of pipelines were located not more than two layers, the expanding space were reserved.	there are three layers, but the air duct was short, maintenance was not influenced.
	Solution	 							
		3D Interference Solution			VO Vertical Overlap, VC Vertical Crossing				
Installation Sequence					Bus way → Chilled & condensed water pipes → Air duct				

activities, and interfaces within various forms of constructions. The complexity associated with interface integration determines the quality of MEP and influences the overall performance of architecture engineering. An increasing number of contractors are becoming aware of this problem, enthusiastically adopting 3D diagrams to simulate the layouts of equipment/pipelines for the integration of interfaces.

The major purpose of this research was to introduce logic to the expert knowledge associated with MEP interface integration. By exercising IIDMS as the main principle in the integration of interfaces, we hope that this method could be used by engineering personnel at all levels of to investigate and resolve the conflicts of integration. Without an automated computer aided system during operations, engineering personnel could utilize the principle of IIDMS to resolve interfacial problems. If computerized 3D and 4D models are available, this principle can be used as a reference of input and output data for modeling. Application of the MEP III principles developed in this study, could reduce the number of meetings between the subcontractors and the professsionals, and reduced overhead at the home office and at the job site.

This research establishes guidelines for MEP III and provides the following contributions:

(1) We defined MEP interfacial components and analyzed the characteristics of MEP interfacial problems to establish the eight criteria for interface integration. Further, by using three elements of construction management, we established the "eight criteria and three-level integration sequencing logic" used as a guideline for the integration of MEP interfaces.
(2) We created a MEP IIDMS model for solving interface conflicts. We combined the "eight criteria and three-level integration sequencing logic" as a mechanism for assessing conflicts. We employed detection, identification, and solution systems to identify and alleviate various interface conflicts.
(3) We provided an IIVT table to verify the integration of the stages of MEP through a practical case, illustrating the results and order of installation.

In the predictable future, MEP systems will move toward automated management systems to resolve conflicts in the construction interfaces. Jobs associated with MEP systems will also follow a reasonable sequence to overcome engineering problems dealing with MEP interfaces. In this manner, overall engineering quality will be enhanced and construction management milestones can be achieved. This study also provides a series of useful guidelines for the integration of interfaces, and procedures and tools for their use in MEP III. The recommendations made in this study can be used as standards of integration when building the construction information management system with the purpose of completing the project on schedule and achieving a desired level of design quality.

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