Knowledge and Reasoning for MEP Coordination

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Abstract: The coordination of mechanical, electrical, and plumbing (MEP) systems is a major challenge for complex buildings and industrial plants. The process involves locating equipment and routing connecting elements for each building system. This multidiscipline effort is time-consuming and expensive and requires knowledge regarding each system over the project life cycle. Current practice requires representatives from each MEP trade to work together to identify and resolve interferences. Effective MEP coordination requires recalling and integrating knowledge regarding design, construction, operations, and maintenance of each MEP system. Currently, designers and constructors use tailored CAD systems to design and fabricate MEP systems, but no knowledge-based computer technology exists to assist in the multidiscipline MEP coordination effort. The paper describes results from a research project to capture knowledge related to design criteria, construction, operations, and maintenance of MEP systems and apply this knowledge in a computer tool that can assist designers and builders in resolving coordination problems for multiple MEP systems.

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Introduction

Mechanical, electrical, and plumbing (MEP) systems, also termed active building systems, are critical to a building's function and must meet performance expectations for comfort and safety. These systems must fit within the constraints of architecture and structure. MEP coordination involves defining the location and routing for components of building systems in what are often congested spaces to avoid interferences and to comply with diverse design and operations criteria (Barton 1983). Ideally, the result of such a coordination effort is the most economical arrangement that meets critical design criteria and performance specifications. The level of difficulty associated with this process directly relates to the complexity and number of building systems in a facility, which have increased in recent years, along with the amount of space available for the systems. Many construction industry professionals have cited MEP coordination as one of the most challenging tasks encountered in the delivery process for construction projects.

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Overview and Research Motivation

The most visible parts of MEP coordination focus on the geometry and functionality of the building systems. However, the coordination process for MEP systems also requires a wealth of functional knowledge regarding MEP systems, their design and installation, and the buildings they serve. For example, the coordination process also involves checking that water lines are not routed above electrical equipment and assuring adequate access for cleaning reheat coils located in ductwork (Korman 2001). Therefore, MEP coordination provides a major opportunity to structure and integrate the knowledge related to multiple project phases into a format that allows users to improve project and building performance.

Our goal for this research was to capture distributed knowledge concerning the different types of systems and represent this knowledge for use by a computer tool designed to provide advice for MEP coordination. To do this, we examined the following question: How can knowledge of MEP systems, derived from all phases of a project life cycle, be represented for MEP coordination and structured to provide reasoning capabilities that identify and assist in resolving coordination problems? The main result of this research is a knowledge framework and reasoning structure that integrates design, construction, and operation and maintenance knowledge of the building systems.

Related Research

Before conducting this research, we investigated other industries that require multidiscipline coordination efforts, use knowledge frameworks and reasoning structures to solve similar problems, and apply current computer technology. We found that most knowledge-based systems focus on one particular phase of the design or construction cycle, as described in the following examples. These examples illustrate how knowledge frameworks and reasoning structures have integrated knowledge to assist designers.

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One of the most notable knowledge frameworks for a task similar to MEP coordination was developed for the design of very large scale integration (VLSI) curcuits. Magic is a sophisticated configuration-layout system for integrated circuits that brings manufacturing knowledge into the design process and uses the Mead-Conway design rules as a basis for integrated circuit design. The design rules allow quick design and checking for violations as the design continues (Taylor and Ousterhout 1984).

Knowledge frameworks, related to construction include work by Fischer, Tommelein, and Chinowsky. Fischer (1993) developed COKE (COnstruction Knowledge Expert), which identified design-relevant constructability knowledge to help designers of concrete structures check for constructability issues during initial design. In his research, he acquired and formalized a large constructability knowledge base for formwork systems and structured this knowledge in a way suitable for the design of reinforced concrete structures. Tommelein developed SightPlan, a tool that employed a knowledge framework and reasoning structure to assist construction managers in configuring temporary facilities on construction sites (Tommelein et al. 1992). The knowledge framework included knowledge about site layout and focused on meeting constraints for layout decision making. Chinowsky (1991) developed CADDIE, a knowledge framework used to assist in configuring the building layout for architectural plans. The framework included design layout knowledge to help architects develop conceptual design diagrams and focused on spatial adjacencies for architectural layout: space planning, acoustics, security, privacy, and daylighting.

This previous research demonstrated successful use of knowledge from specific disciplines. We built on these prior research efforts in developing a tool to apply knowledge from multiple disciplines and project phases to identify problems, first by identifying multiple types of interferences, and then by providing advice for resolving coordination problems. The scope of the research included heating and ventilating, plumbing, electrical, and other specialized systems for commercial and institutional buildings.

Research Method and Activities

The portion of the research described in this paper first involved acquiring, analyzing, and representing knowledge and then developing a knowledge framework and reasoning structure.

Acquiring, Analyzing, and Representing Knowledge

This research used four major approaches to acquire knowledge regarding MEP coordination: review of written information sources, personal interviews with experts in the field, observations of experts working in project meetings, and work experience MEP coordination for an entire project.

Acquiring knowledge first began with identifying information critical to MEP coordination. Since very little published information is available about MEP coordination, this research focused on collecting data from current and completed construction projects. Through interviews with architects, engineers, general contractors, and specialty contractors we identified the knowledge required for each building system and major component involved in MEP coordination and acquired knowledge about the design, construction, operations, and maintenance phases of a project. The results of these interviews provided a basis to identify the component attributes (functional, geometric, and other characteristics) needed for coordination.

Table 1. Geometric Characteristics

Coordinate information	Component dimensions	Connections
X_{max}	Height (diameter)	Number of vertical connections per length
Y_{max}	Width (diameter)	Number of horizontal connections per length
Z_{max} (top elevation)	Length	Overall line length
X_{min}	Cross-sectional area	—
Y_{min}	—	—
Z_{min} (bottom elevation)	—	—

Analyzing the knowledge entailed determining when and why a specific system would have priority over another system in a specific area of a building or facility. This included describing how engineers determine priority among systems during different project phases. It was also important to compare requirements of various design disciplines as well as to set priorities based on the following criteria: complying with geometric constraints, meeting design intent, considering installation requirements, and addressing maintenance concerns. This process laid the foundation for the reasoning structure described below.

Representing the knowledge first required classifying knowledge into the categories mentioned above: design, construction, operations, and maintenance. Good representation of knowledge should make knowledge very explicit and expose natural constraints inherent to the problem being solved (Hunter 1993). The knowledge representation entailed developing an object hierarchy that included the most common components of building systems (for example, fans, ductwork, pumps, pipes, chillers, electrical raceway), which included data regarding the object characteristics found in Tables 1 and 2.

Developing Knowledge Framework and Reasoning Structure

Knowledge frameworks are structured sets of knowledge organized into sets of packages so that, given an appropriate situational context, the knowledge framework and reasoning structure can propose a decision about what is possible or what might happen next (Galambos 1986). Developing a knowledge framework from large domains is difficult; the larger the domain, the more difficult it becomes to create a reasoning structure (Carrico 1989). Therefore our objective was to develop a knowledge framework for MEP coordination that reflected the complexity and variety of all the components, yet remained simple enough to facilitate decision making and assist in problem solving.

The development of the knowledge framework included structuring an object hierarchy or list of components and fundamental blocks of knowledge. We included design-intent knowledge, construction knowledge, and operations and maintenance knowledge in the knowledge blocks, which included specific information about each component in the form of object attributes. The layout

Table 2. Topological Characteristics

Location	Spacial relationships	Spacial adjacencies
Is located in room...	Is part of system...	Is located next to (left or right)...
Is located in facility...	Is connected to...	Is located above...
—	—	Is located below...

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of the knowledge framework is important because it determines how the represented objects interact with each other in the reasoning structure.

Reasoning structures found in knowledge-based systems often perform diagnostic tasks and typically use the following methods: heuristics, model-based reasoning (MBR), and case-based reasoning (CBR) (Kunz et al. 1995). Since the intent of this research was to assist engineers in coordinating MEP systems at the design stage, we needed to select a method that was able to match the human process for resolving coordination conflicts. This required heuristics and MBR to provide the necessary feedback for MEP coordination, described later in the paper. We used the MEP knowledge framework by applying tailored solution classes and generalized heuristics to provide advice regarding coordination problems.

Heuristics provide a basis for reasoning mechanisms in classic expert systems. Heuristic classification systems work by abstracting measurable data and relating them to a predefined potential problem (Kunz et al. 1995). The system matches the problem with a solution and then refines the solution. Heuristics are able to represent many different kinds of knowledge and may express fundamental principles, experimental rules of thumb, or high-level knowledge (Dym and Levitt 1991). In this research, we chose heuristic reasoning because it allows identifying and resolving coordination problems by classifying the coordination conflicts and selecting a solution refinement mechanism to resolve the conflicts. Due to the need to spatially rearrange components of building systems during MEP coordination, we also used MBR as described later in the paper.

MBR involves creating a product model to form the basis for the reasoning mechanism. This gives MBR the ability to abstract graphical, geometrical, topological, and behavioral characteristics from the components in the model for the reasoning processes (Kunz et al. 95). In this research, the geometric representation served as the model. MBR provided the means to create a virtual representation of the building systems and a basis for decision making. Groups of individual components from each building system collectively comprise the product model.

Knowledge Framework and Represention for MEP Coordination Knowledge

The knowledge framework and reasoning structure for MEP coordination uses the multiple types of knowledge to evaluate and coordinate the configurations of MEP systems. This research proved that three knowledge bases or domains have a great impact on MEP coordination: design, construction, and operations and maintenance. The knowledge collected for each domain assists in MEP coordination. The most pertinent aspects of each domain are described later in the paper. Fig. 1 provides an overview of the type of knowledge collected in the knowledge framework.

Design Criteria and Intent, Construction, and Operations and Maintenance Knowledge

Design knowledge is applied during MEP coordination to assure that the systems satisfy performance requirements for the specific project and comply with codes and standards. Design engineers and detailers bring design knowledge regarding each type of system to the MEP coordination process (Tatum and Korman 2000).

Construction knowledge includes fabrication, installation, and sequencing considerations as well as requirements for start-up,

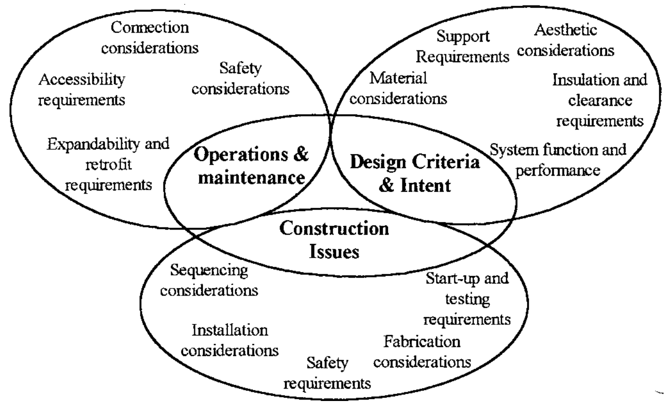

Fig. 1. Knowledge bases required for MEP coordination

testing, and safety (Korman 2001). Superintendents, foremen, and engineers familiar with field operations provide this knowledge during MEP coordination to assure feasible designs for building the systems and to increase the efficiency of field operations.

To minimize the cost of operation and maintenance or to decrease the difficulty and cost of system renovation, MEP coordination must also consider the phases of the facility life cycle that follow construction completion. The knowledge these constraints add to the coordination of MEP systems comes from facility managers, building engineers, and the maintenance staff.

The three sections of Table 3 list the attributes of MEP components related to the design criteria and intent, construction phase, and operations and maintenance. The table also includes an example of each attribute. The knowledge framework therefore identifies the requirements that MEP systems must satisfy over their complete life cycle. The reasoning structure applies this knowledge to identify problem areas and provide advice for solution.

Reasoning Structure for MEP Coordination

The prototype tool developed in this research uses a reasoning structure to apply the knowledge described previously. The following section describes the reasoning performed by the tool and then defines the types of interferences identified in the process along with the component attributes and solution classes involved. Two essential parts of the reasoning structure are used in this research: model-based reasoning (MBR) and heuristic reasoning. This section describes each and how the tool uses them to identify and help solve problems in MEP coordination.

Model-Based Reasoning

Because MEP coordination is in large part a configuration task, it depends heavily on the geometric and topological characteristics of the components represented in the geometric model (Korman 2001). Therefore, the reasoning structure uses MBR to abstract geometric and topological data from the geometric model and then determines the spatial relationships between components in the model.

Geometric characteristics are those properties of a component that express dimension and location, such as height, width, and length. Topological characteristics of components indicated spatial information between components, such as their spatial relationships in the geometric model (Fischer and Tatum 1997). MBR

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Table 3. Knowledge Related to Design, Construction, and Operations and Maintenance

Knowledge base	Attribute name	Description	Example
Design criteria and intent	Function	Designates primary performance function of component	A light fixture illuminates; a sprinkler head sprays water
	System	Designates system to which component belongs	A slot diffuser belongs to HVAC dry system; a heating water return pipe belongs to HVAC wet system
	Material type	Designates material or choices of material used for specific component	Choices for supply air duct material include aluminum, galvanized steel, sheet metal, stainless steel, or fiberglass
	Material cost	Designates cost of component (per vendor data or estimating standards)	Sprinkler line fabricated from 2 in. diameter black steel pipe costs $1.57 per linear foot
	Support system	Designates typical system used to support component	Electrical conduit may rest on pipe racks that contractors attach to walls or hang from trapeze hangers
	Insulation	Designates insulation type and thickness of particular component; possible types include fire protection, thermal energy conservation, sound isolation, antisweat, and personnel protection	Insulation thickness required for heating water supply lines is 1 1/2 in.
	Clearance	Designates design clearance requirements of components to prevent heat exchange, mitigate vibration concerns, or minimize signal crossing in communication lines	Required clearance between heating water supply and heating water return lines is 6 in.
	Slope	Designates required slope for component	Gravity-driven wastewater drain lines should slope 1/8 in. per foot
Construction	Installation space	Defines and reserves space for installation of components; this includes space around component for construction craft persons, materials handling and storage, and construction equipment	Pulling electrical cable requires 5 ft of access space from end of conduit
	Installation sequence	Designates typical installation of components considering start-up, testing, commissioning, and turnover requirements to maximize prefabrication	Installation of air terminal boxes always precedes air distribution ducts to zone
	Lead time	Designates average lead time for fabrication of component	VAV boxes typically require lead time of 2 weeks
Operations and maintenance	Access Space	Defines and reserves space required for operations and maintenance	Access space required by personnel for valves is typically 12 in., depending on type of valve
	Access frequency	Designates access frequency required to maintain component	Expected access to sprinkler heads is once per month

allows the reasoning structure to maintain updated knowledge concerning the size and dimensions of components as well as the location of each component and its position relative to other components, known as spatial adjacencies. Tables 1 and 2 identify geometric and topological characteristics that the reasoning structure abstracts from the geometric model for each component.

Heuristic Reasoning

Heuristic reasoning provides a basis for determining and resolving coordination conflicts by abstracting measurable data and relating it to a predefined potential problem. It helps resolve coor-

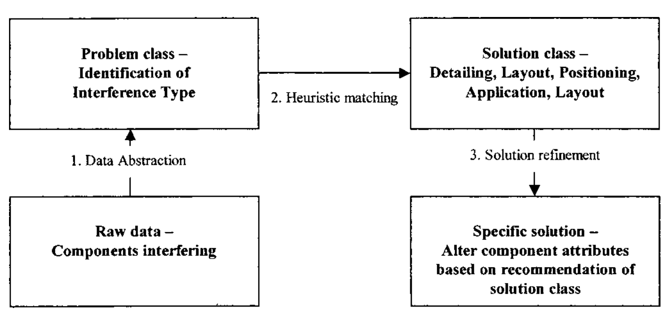

Fig. 2. Heuristic reasoning structure

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Table 4. Type and Description of Interference Identified by Reasoning Structure

Interference type	Description
Actual	Actual (physical) interference occurs when two or more components physically interfere
Extended	Extended interference occurs when component interferes with extended space (such as access path for maintenance) that is associated with another component
Functional	Functional interference occurs when engineers position two or more components such that their location in relation to each other jeopardizes intended function of component, such as a pipe blocking light from a fixture
Temporal	Time-related interference occurs when engineers position components in a manner that prevents efficient construction sequencing and scheduling
Future	Future interference occurs when engineers position components in locations that do not allow space for routine operations and maintenance tasks or space for future expansion

dination issues for a specific type of interference, as described in the next section. Fig. 2 displays how heuristic reasoning helps to determine and resolve coordination conflicts.

When components in the geometric model interfere, their component attributes are abstracted to determine what type of interference exists: actual, extended, functional, temporal, or future (Table 4). By using heuristic matching, the reasoning structure identifies one of the following solution classes: detailing, layout, positioning, application, or scheduling. Once the system determines the solution class, it proposes a solution set through solution refinement. Designers can then select the specific solution that makes the most sense in their view. Each of these steps—data abstraction, heuristic matching, and solution refinement—is described in more detail in the following sections.

Data Abstraction—Identification of Types of Interference

As a part of analyzing the knowledge obtained from observing experts during coordination meetings and other sources, we were able to identify and classify the five most common types of interference found in MEP coordination. Table 4 defines these interferences.

The reasoning structure identifies interferences by evaluating the attributes of each component in the geometric model and is able to identify instances of each type of interference listed in Table 4. For instance, when the insulation of one component interferes with another component in the geometric model, the reasoning structure classifies the interference as an actual interference. Most current commercial computer-aided-design tools can identify only actual interferences, and only a few are able to identify extended interferences. However, to obtain effective coordination results, one must also consider functional, temporal, and future interferences during MEP coordination.

Heuristic Matching Process

After classifying the types of interferences found in the geometric model, the reasoning structure uses heuristic matching to determine a general solution for resolving the interference. This section identifies the solution classes available and the applicable component attributes. Following this, we describe the process of solution refinement and give an example.

Section of Solution Classes

This research identified five classes of solutions used to resolve coordination problems: detailing, layout, positioning, application, and scheduling. The detailing solution class is used to modify detailed design of components, such as size, insulation, and support system; the layout solution class is used to move components along their horizontal plane; the positioning solution class is used to move components along their vertical plane; the application solution class is used to alter design intent and performance of components; and the scheduling solution class is used to adjust installation sequence and scheduling related attributes.

The reasoning structure developed in this research uses the component attributes to identify interferences and select possible solution classes. Heuristic matching relates the component attributes to the appropriate solution classes, which provides the basis for the reasoning structure to provide advice regarding coordination problems.

Solution Refinement—Selection of Specific Solution

After identifying the possible solution classes that are available for interference resolution, the reasoning structure suggests a specific solution. Heuristics associated with each solution class provide a mechanism for resolving interferences. Table 5 defines and groups the types of heuristics by solution class.

Heuristic Reasoning Example

Fig. 3 depicts the use of the heuristic reasoning structure for a particular example. Two components interfere: a pressurized domestic water supply line and a gravity-driven waste line. The reasoning structure classifies this interference by evaluating the attributes and characteristics for each type of interference. In this case, the two components are found to physically interfere due to the overlap of the geometric coordinates. Therefore, the reasoning structure first classifies the interference as an actual interference. However, upon further evaluation of object attributes and characteristics, the reasoning structure determines that the slope attribute of the gravity line is actually causing the interference. Therefore, the reasoning structure classifies the interference as a functional interference (Step 1).

Using heuristic matching (Step 2), the reasoning structure selects the relevant solution class set. The table indicates that the solution class set includes layout, positioning, and application, which indicates that the solution will involve moving one of the components along the horizontal or vertical plane or considering the design intent attributes of the components. Using Table 5, the solution refinement (Step 3) indicates that the heuristic that best matches this case is functionality. This heuristic states that "pressurized components shall yield to other components, and gravity-driven components shall have priority." Therefore, the specific solution for this coordination issue is to move the pressurized domestic water supply line.

As described above, the knowledge framework and reasoning structure are both detailed and robust. The knowledge framework is a compact classification of component attributes sorted by

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Table 5. Heuristics Associated with Detailing Solution Class

Solution class	Heuristic name	Explanation
Detailing	Supportability	• Components with larger support systems should have priority
		• Components with greater number of vertical supports should have priority
		• Components that require seismic bracing should have priority
Layout (horizontal)	Functionality	• Locate components with slope requirements next to other components with slope
	Accessibility	• Locate components with access space requirements in corridor spaces
	Relative cost	• Locate components with greater cost and greater number of lateral connections, next to penetrations to minimize number of connections needed for branch lines
	Relative size	• Locate components with greater cross-sectional areas (width×height) next to column lines
Positioning (vertical)	Functionality	• Locate components with slope requirements above or below components with similar slope requirement
	Accessibility	• Locate components with no access space requirements should be above other components
		• Locate components with greater access frequency below other components
	Relative cost	• Locate components with greater cost and greater number of vertical connections below other components
	Similarity	• Locate components with similar access space requirements above or below each other in vertical plane to reduce horizontal space
	Perpendicular path	• When perpendicular components interfere, component with greater overall line length should yield to other components
Application	Functionality	• Pressurized components shall yield to other components
		• Gravity-driven components shall have priority
		• Components critical to process in room shall have priority
Scheduling	Installability	• Locate components later in installation sequence below other components unless they are connected
		• Locate components with greater lead time below components with shorter lead time
	Connectability	• Components with greater number of vertical connections should have priority
		• Components with greater number of horizontal connections should have priority
	Relative size	• Locate components with greater cross-sectional areas (width×height) and greater length above other components and directly below primary structure for ease of installation
	Relative length	• Locate components with greater length or overall line length above other components for ease of installation
	Similarity	• Locate components with similar lead times adjacent to other components with same lead time

project phase: design, construction, operations, and maintenance. The reasoning structure uses the knowledge framework by applying tailored solution classes and generalized heuristics to provide advice regarding coordination problems.

Conclusions and Practical Applications

Current practice involves inconsistent use of fragmented knowledge to perform MEP coordination. As mentioned previously, there was no published background about the knowledge required for MEP coordination. The results of this research provide an organized structure of the knowledge and reasoning necessary to perform MEP coordination. Collecting, analyzing, and representing the knowledge needed for MEP coordination resulted in a framework tailored to the needs of those involved in this important process. We have formed several conclusions regarding the knowledge framework and reasoning structure developed in this research, needs for future research, and practical applications of this research.

Lessons Learned from Developing Knowledge Framework and Reasoning Structure

For the most part, the knowledge framework contained the knowledge necessary to perform coordination. We specifically limited the number of components represented in the object hierarchy by ignoring components not commonly associated with MEP systems or coordination. The knowledge structure focused directly on those components most pertinent to MEP coordination. In addition, we paid special attention to the reasoning structure and its relationships to the knowledge framework. However, we found that we did not represent routing knowledge sufficiently in the knowledge framework. Such knowledge should be studied and formalized in future research. Despite the deficiencies, the knowledge framework contained sufficient component attributes to demonstrate its effectiveness.

The reasoning structure developed in this research always bases priority decisions on technical data. Specialty contractors often negotiate regarding which components will have priority. For example, one specialty contractor may negotiate by saying, ‘‘I will move here, if you move there!’’ This may occur without any

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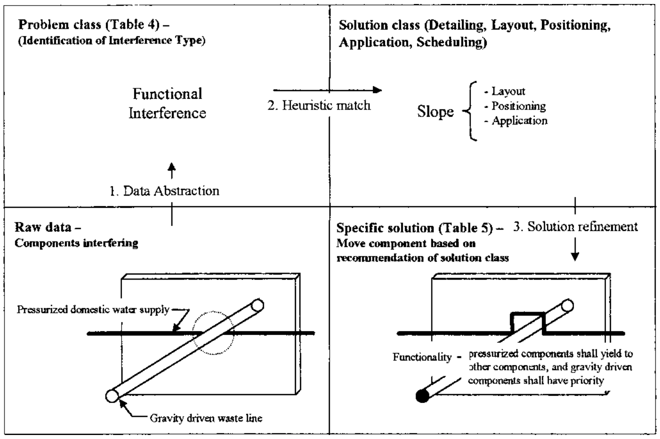

Fig. 3. Heuristic reasoning example

technical data at all. Participants know that the coordination process must resolve all interferences, or else they will have to deal with the interferences during construction. The reasoning structure developed in this research provides the technical rationale for resolving interferences. Participants in the actual coordination process may, of course, also apply other criteria in making these decisions.

Needs for Future Research

The research results provide a good starting point for continued investigation of knowledge related to MEP systems. Priority topics for future research should include the ability to provide design calculations and to optimize space use for MEP systems.

Often installers must make decisions in the field that affect the design of a system, for example, increasing or decreasing an HVAC dust size to meet a clearance requirement. These decisions may affect the performance of a system, for example, increasing the static pressure and airflow in the duct. The knowledge framework developed in this research does include the knowledge needed to resize or reroute parts of the MEP systems. Its knowledge only provides recommendations and gives feedback for arranging the building system during the initial coordination effort. Extending the knowledge framework and reasoning structure to perform design calculations would be a useful and logical step. This would enable MEP designers and constructors to expedite coordination efforts even further than possible with the system developed in this research.

Another logical extension of this research is to add reasoning for optimizing space use. This would enable architects to reduce story heights, thus potentially reducing overall building costs and may even allow architects and constructors to create more usable space within the building envelope by further considering MEP systems. From what we have learned in this research, this future work would entail enhancing the knowledge framework and reasoning structure by extending the use of heuristics for space allocation and optimization. This would require the development of optimization algorithms that consider each project phase—design, construction, and operations and maintenance, which would allow planning teams to use the reasoning structure to consider the implications of decisions made during schematic design on all building systems.

Practical Applications

The current practice for MEP coordination is slow and expensive. Completed by manual means, MEP coordination requires considerable time from scarce experts who have specialized knowledge about the design, construction, and operation and maintenance of these systems. The current work process offers major opportunities to improve.

This research provides important results that can improve practice. Industry professionals recognize the need to use information technology and to revise the MEP coordination work process. This research also provides a foundation for a computer tool that allows knowledge recall from design, construction, and operations and maintenance to aid in preliminary design analysis and provide valuable insight to engineers and construction personnel about design criteria, efficient construction, and suitability for facility operation.

Our proposal for a revised work process would begin with specialty contractors forwarding their respective drawings (that is, mechanical, electrical, plumbing) to a drawing coordinator who would integrate the files to create a composite model representing the building structure and individual MEP systems. A knowledge-based computer tool, developed from the knowledge framework and reasoning structure, would then analyze the composite model to identify and resolving multiple types of interferences. This would involve verifying satisfaction of critical design criteria, evaluating for constructability, and addressing operation and maintenance concerns. After analysis, review of the results could occur electronically, followed by distribution to the individual specialty contractors for fabrication and installation. Following fabrication and installation, the contractor could update the composite model to include any changes made in the field during construction, thus benefiting the operation and maintenance of the facility. The revised model would then become the life-cycle model for the facility.

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