CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Development of a Knowledge-Based System to Improve Mechanical, Electrical, and Plumbing Coordination

By

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SUMMARY

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Abstract

Mechanical, electrical, and plumbing (MEP) coordination is a major challenge for complex buildings and industrial plants. It involves locating equipment and routing connecting elements for each system using a process of sequentially comparing and overlaying transparent drawings of MEP systems on a light table to detect spatial interferences. This multi-discipline effort is time-consuming, expensive, and requires knowledge regarding each system over the project life.

Currently, designers and constructors use tailored computer tools to design and fabricate MEP systems, but no knowledge-based computer technology exists to assist in the multi-discipline MEP coordination effort. Effective MEP coordination requires recalling and integrating knowledge regarding design, construction, operations, and maintenance of each MEP system.

The research investigators believed that the use information technology could significantly improve the current process. Hence, the purpose of this research was to develop a technology that integrates a number of knowledge bases – design criteria, construction, operations, and maintenance – into a knowledge-based system that is able to provide valuable insight to engineers and construction personnel, as well as assist them in

resolving coordination problems for multiple MEP systems.

This research focused on the following key questions: How can knowledge of MEP systems, derived from all phases of a project lifecycle: a) be represented for MEP coordination? b) be structured to provide reasoning capabilities that identify and assist in resolving coordination problems? and c) be applied to demonstrate use of computer technology? By acquiring knowledge from industry experts and using symbolic modeling methods, this research resulted in three major contributions. First, it increased the understanding of current practice and problems associated with coordinating building systems. Second, it provided a knowledge framework and reasoning structure that uses the knowledge required for MEP coordination. Third, it demonstrated the technical feasibility of developing a tool to assist in performing MEP coordination.

The prototype tool developed by the research investigators provides a foundation for future researchers to develop additional tools to assist in multi-discipline coordination efforts. This information technology provides a basis for industry leaders to create a revised work process for MEP coordination.

This report describes the research completed by C.B. Tatum and Thomas M. Korman at Stanford University's Center for Integrated Facility Engineering (CIFE). This research supports CIFE's goals by increasing horizontal and vertical integration over the life cycle of a facility and furthering the development of advanced technologies that improve the productivity and quality of the AEC industry through increased automation.

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Chapter 1 – Research Need and Objectives

1.1 Introduction

Mechanical, Electrical, and Plumbing (MEP) coordination is the arrangement of components for various active building systems, which are critical to a building's function and must meet performance expectations for comfort and safety. Building system components must also fit within the constraints of architecture and structure. Coordination is a process that involves defining the locations for components of building systems, in what are often congested spaces, in order to avoid interferences and to comply with diverse design and operations criteria. 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 in recent years has increased [Sanchez 98]. As shown in Table 1.1, building systems can now range from 15 to 60 percent of the total building cost.

Table 1.1 - MEP systems as a percentage of total building cost [Tao 01]

Facility Type	MEP cost as a percentage of total building cost		
	High	Medium	Low
Semiconductor plants	60	50	40
Biotechnology plants	65	55	45
Heavy industrial plants	60	50	40
Hospitals	50	40	30
Commercial office buildings	40	30	15
Multi-residential complex	25	20	15
Research laboratories	50	40	30

While estimators can quantify the building systems cost, the cost associated with coordination is more difficult for estimators to quantify. One general contractor estimated that MEP coordination could cost as much as six percent of an individual building system [Sanchez 98]. An electrical contractor noted that coordination cost equals design cost on projects in Silicon Valley. Each is about three percent of the total cost for electrical systems [Bergthold 98].

Many construction industry professionals have cited MEP coordination as one of the most challenging tasks encountered in the delivery process for construction projects. There are three primary reasons for this. First, the process is highly fragmented between design and construction firms. Second, the level of technology used in different coordination scenarios varies significantly. Third, the current manual process does not provide a facility model for use over the complete life cycle.

1.1.1 Current Process and Results

The current work process for MEP coordination begins with design consultants, or design-build contractors who perform design, designing their systems independently. They generally prepare diagrammatic drawings indicating the required equipment and a path for the connecting elements of their system. Once engineers complete the system designs, the coordination process begins with meetings involving each of the specialty contractors (e.g., Heating Ventilation and Air Conditioning (HVAC) ductwork and piping, process piping, plumbing, electrical, fire protection, controls). These specialty contractors eventually fabricate and install these systems. (See Figure 1.1.)

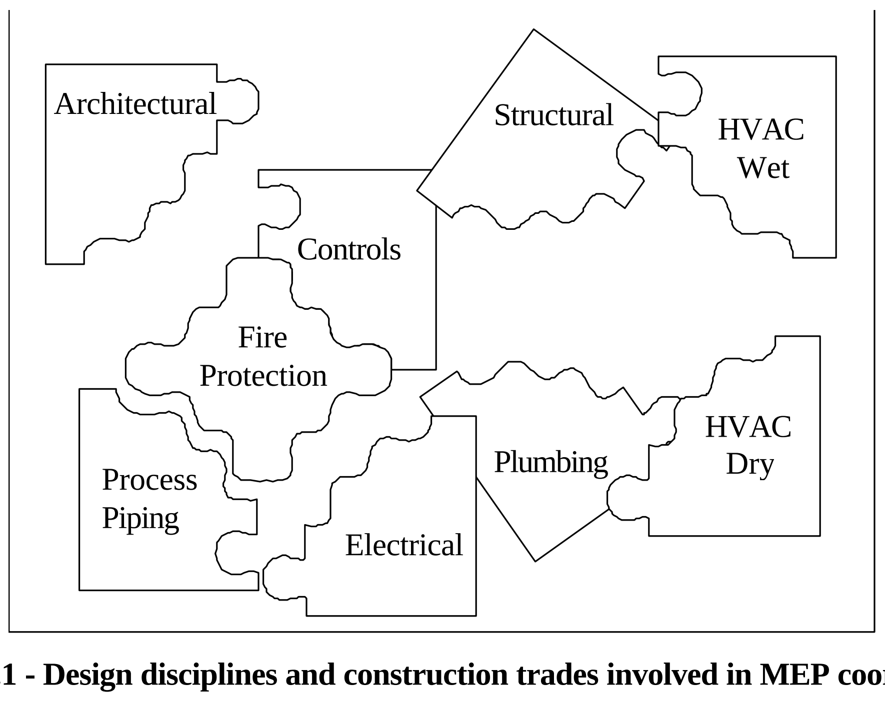


Figure 1.1 - Design disciplines and construction trades involved in MEP coordination

The specialty contractors provide 1/4 inch per foot scale plan-view layouts of their building systems using transparent drawings media. They then compare these transparent plans over a light table that allows viewing two or more drawing sets at once. The comparison process involves locating each building system within the architectural and structural envelope and with respect to each of the other building systems. Furthermore, the process seeks to determine if the systems comply with design, construction, operations, and maintenance criteria. Specialty contractors carefully checking for fit within the allowable space and physical interferences, determining if field installation is possible, and noting any configurations that may adversely effect operations and maintenance.

This process often involves frequent and taxing meetings. It is difficult to visualize complex systems in congested spaces. This may require drawing multiple section views to accompany the plan views. Furthermore, it is also very difficult to accommodate design changes after contractors make coordination decisions. The process is slow and expensive, and can add significant cost to a project and delay the start of construction.

1.1.2 Problem Areas

Accelerated project schedules and decreased designers' fees do not allow detailing of MEP systems by design consultants. Therefore, the scope of work for specialty contractors increasingly includes "design assist" to complete the design for fabrication and installation. The less complete definition of systems in the "design assist" approach makes it very difficult to define the scope of fabrication and installation. Vague scope increases the potential need for contract changes.

There is wide variation in the level of technology used in the MEP coordination process. At the low-tech end of the spectrum, specialty contractors draft plan-views on translucent media and prepare section-views when necessary. At the other extreme, progressive contractors have used 3D CAD to improve the process. One example of this is the use of electronic plant models, with major benefits on large hydrocarbon and power projects, where an Architect/Engineer completes the entire design. However, design consultants and specialty contractors prefer computer-aided design systems that are tailored to provide specific information for detailing, estimating, fabricating, and tracking their specialty work. Current use of multiple systems (e.g., AutoCAD™, QuickPEN™, MultiPIPE™) tailored to the needs of specific disciplines and trades limits overall effectiveness. The systems are not compatible and electronic data transfer between them usually results in a loss of about ten percent of the data content. There is definitely not a lack of technology, but there is a need to better apply the available technology tailored to a specific set of business and technical conditions.

Lack of a facility model has always been a major problem for operations and maintenance personnel. Following construction, operations and maintenance personnel are left to operate building systems in congested spaces, often with complex configurations that were difficult to visualize during the coordination process. One example of this is not providing adequate space for a particular building system and causing inefficient construction as well as adverse operating and maintenance conditions. The lack of a facility model increases the potential for problems and the need for effective coordination between the multiple systems.

1.1.3 Improving the current process using computer technology

The problems mentioned above present a major opportunity to improve project performance, creating a revised work process, through increased integration and use of information technology.

Object-oriented 3D models and knowledge based reasoning systems are two forms of integration that allow for a revised process of coordination. Object-oriented 3D models allow associating knowledge with objects represented in 3D. A knowledge-based reasoning structure is a set of rules with logic equations that use the object attributes in the 3D model to assist a user in making informed decisions.

The use of object-oriented 3D models and a knowledge-based reasoning structure can assist the MEP coordination process by creating a revised work process. Increased horizontal integration could improve the effectiveness of the coordination process and help better meet project objectives. The result can allow precisely locating components of building systems while meeting multiple design objectives and criteria, facilitating efficient construction, installation, and commissioning, and satisfying operations and maintenance requirements. However, current results of MEP coordination efforts do not entirely satisfy these objectives.

As stated above, my vision is to capture the distributed knowledge concerning the different types of systems and represent this knowledge for use by a computer tool to meet the special needs of MEP coordination. To do this, I have examined the following key questions. How can knowledge of MEP systems, derived from all phases of a project lifecycle:

a) be represented for MEP coordination?
b) be structured to provide reasoning capabilities that identify and assist in resolving coordination problems?
c) be applied to demonstrate use of computer technology to assist with MEP coordination?

Representing the knowledge regarding each particular system required for MEP coordination involves understanding the special needs of design, construction, operations, and maintenance. This requires understanding the types of problems that arise during MEP coordination and as well as how to resolve the problems. Furthermore, this necessitates knowledge of what experts consider good coordination.

This first requires classifying knowledge into the categories mentioned above – design, construction, operations, and maintenance. Following the classification process, knowledge engineers must structure the knowledge to allow diverse reasoning capabilities. This entails developing an object hierarchy that includes the most common components of building systems and object attributes for each component.

Applying knowledge to demonstrate the ability to use a computer tool requires developing a reasoning structure that utilizes the knowledge to perform example functions such as locating systems to avoid interferences and segregating specific systems based on safety concerns. Other possible functions include optimizing the functional performance of a system, locating the systems to promote efficient construction, and arranging system components for ease of operations and maintenance purposes.

1.2 Research Purpose and Objectives

The purpose of this research was to increase understanding of MEP coordination and the knowledge it requires. With this new understanding, I sought to demonstrate the feasibility of capturing and using this knowledge in a computer tool that could provide advice during the process. Therefore, the following objectives, further described below, structured the research process:

- increase understanding of current practice for MEP coordination
- develop a knowledge framework and reasoning structure for the MEP coordination process
- demonstrate the technical feasibility of representing and applying the knowledge in a tool to assist with MEP coordination
- provide recommendations for further research and practice.

1.2.1 Increase understanding of current practice

Describing current practice is essential if we are to understand MEP coordination. Significant work toward this objective was completed under an initial CIFE seed project, "Improving MEP Coordination of Building and Industrial Projects" [Tatum 99]. The major findings described the parties involved in MEP coordination, the technology used, and the current process, which I termed the Sequential Comparison Overlay Process (SCOP), and the reasoning behind the current practice.

Owners use many types of project delivery processes and construction contracts for MEP work, including design-bid-build, design-assist-build, and design-build. This research identifies differences in MEP coordination between these contract types by answering the following questions. Who is responsible for MEP coordination? How do the individuals interact in these different settings? Chapter 2 summarizes findings regarding these questions.

The level of technology currently used in the process varies greatly. Drawings produced by architects, engineers, and detailers vary from schematic one-line drawings to fully detailed drawings with referenced cross-section views. Many questions arise from such varying levels of detail: At what stage in the design process can designers make decisions concerning coordination issues? Do designers need to complete design to begin coordination? What aspect or portion of a system should designers complete to begin coordination? What equipment must designers select to allow the coordination process to begin? Is it necessary to size components such as conduits, ducts, and fire sprinkler lines to perform MEP coordination? What level of component representation in 3D CAD is required to perform MEP coordination? Chapter 6 will pursue such questions.

Chapter 2 describes the current process. I explain the considerations contractors encounter during coordination and how they resolve conflicts. This background is very important in understanding the reasoning for key decisions. Therefore, part of the objective regarding current practice was to understand what each party, including design consultant, specialty contractor, general contractor, and owner, seeks to gain from the coordination process.

1.2.2 Develop a knowledge framework and reasoning structure

Knowledge frameworks are structured sets of knowledge. Knowledge engineers organize the sets of knowledge into 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 86]. Therefore, my objective to develop a framework for the knowledge used in MEP coordination required understanding what knowledge is important. By querying the knowledge framework, it is possible to diagnose, decide, and solve problems [Iyer 95]. In developing a knowledge framework for MEP coordination, I identified the types of decisions involved and the information they require. This guided knowledge acquisition, formalization, and representation.

In order to develop an effective tool for MEP coordination, I developed a knowledge framework that included an object hierarchy. The object hierarchy allowed the knowledge framework to categorize the components commonly found in building systems, and information regarding each component, known as object attributes. The object attributes contain specific information about each component. Representation of the object hierarchy and object attributes is the basis for developing a knowledge framework for the MEP coordination tool. Activities related to this objective resulted in a representation of the knowledge, which provided the basis for developing the tool to assist in MEP coordination. I discuss developing the knowledge framework in Chapter 4.

1.2.3 Demonstrate the technical feasibility of representing and applying knowledge

Chapter 7 describes two test cases that I conducted to evaluate using the knowledge framework and reasoning structure to assist in MEP coordination. I compared the results of the test cases with the results of actual coordination efforts. This research shows how using a knowledge-based 3D tool improves the MEP coordination process by providing advice regarding the design, installation, and life cycle of MEP systems. The prototype tool can improve the results of coordination meetings by helping designers, contractors, and operations personnel consider different types of knowledge and design constraints during the coordination process.

I designed and managed the development of a prototype MEP coordination in JAVA™, an object-oriented symbolic modeling language composed of 3D objects. These 3D objects represent components in the facility. Each component in the model includes associated knowledge, referred to as component attributes. The product of the activities related to this objective was a prototype version of the tool, which can provide a basis for future commercial development. To test and validate the tool, I used actual retrospective and prospective test cases. Chapter 7 provides further details and findings from these test cases.

1.2.4 Provide recommendations for future research

This research contributes to the overall understanding of current practice and problems associated with MEP coordination by formalizing the knowledge required in the process and demonstrating the technical feasibility of developing a tool to assist. These research contributions further described in Chapter 8, led to several recommendations for future research. These include optimization of space for building systems, modular design of building systems, investigation of cost and schedule implications, and coordination in spaces other than buildings.

Finally, the practical aspects of this research resulted in specific recommendations for industry. Chapter 8 includes these recommendations, along with a plan for implementing the prototype tool and a description of how to revise the work process to best use the new technology. This section considers how and by whom the tool can be used, what effect it will have on a projects' contractual agreements, and how to commercialize the tool.

1.3 Reader's Guide

Chapter 2 describes the current process for MEP coordination, including differences in projects using different delivery approaches. Chapters 3 and 4 define the methods used for this research and summarize the relevant background. Chapter 5 defines the capabilities and knowledge required for the MEP coordination tool and the revised work process to use it. Chapter 6 describes the knowledge that the tool contains. Chapter 7 gives the results of the two test cases of the tool. Chapter 8 highlights the contributions and recommendations regarding the use of a tool to improve MEP coordination.

Industry practitioners may receive the most benefit from reading Chapters 2 and 7, which focus on the past, present, and future of MEP coordination by describing current practice and the two cases used in the research. For research purposes, Chapters 3, 4, and 8 are most relevant because they define the research methods and describe the key research activities. In addition, Chapter 8 highlights contributions made by this research. Software developers will find Chapters 5, 6, and 8 to be the most useful; these chapters describe the knowledge base and reasoning structure.

Chapter 2 – Current Practice for MEP Coordination

Understanding current practice for MEP coordination is essential to recognizing the opportunity to improve and to develop effective computer tools that support improved processes. Recognizing fundamental constraints from industry organization is essential to developing a computer tool with potential for implementation. This chapter presents a description of current practice based on interviews with architects, engineers, general contractors, and specialty contractors who have extensive experience with MEP coordination. It also includes information gained during observation of several MEP coordination meetings.

2.1 Overview of current practice

This section defines MEP coordination, describes current practice and the parties involved, and identifies key problems.

2.1.1 Definition of MEP coordination

Coordination is an integral part of many activities during the life of a construction project. In fact, the entire construction process requires coordinating key resources such as information, material, equipment, and labor. Many coordination activities relate to MEP systems. A few are as follows:

- integration of MEP systems into the architectural and structural envelope
- integration of detailed MEP trade drawings
- creation of equipment matrices and selection of suppliers
- installation and procurement scheduling for MEP systems
- acquisition of supplier drawings for components of MEP systems
- tracking and formalizing procedures for submittals
- general contractor's management of MEP specialty contractors.

MEP coordination is only one link in the chain of coordination events. It is the arrangement of various building system components, which are critical to the building functioning properly. The system components must fit within the constraints of the architecture and structure as well as meet the performance expectations for comfort and safety. The MEP coordination process involves defining the exact location for each building system component throughout the building to comply with diverse design and operations criteria. Often contractors must arrange components in congested areas to avoid interferences with architecture, structure, and other building system components.

A major finding of this research was identification of the Sequential Comparison Overlay Process (SCOP), which is a multi-disciplinary effort with input from many people. Iterative in nature, the process requires many revisions. This process occurs only after engineers have completed preliminary design drawings and results in a final set of coordination drawings. Section 2.5.2 describes this process in more detail.

2.1.2 Description of current practice

Currently, MEP coordination begins after design and preliminary routing of all building systems (mechanical, plumbing, electrical, etc.). The design is complete when engineers have sized all components (e.g., conduits, pipe, HVAC duct), completed the engineering calculations, and produced the diagrammatic drawings; however, engineers have not defined specific routing. Usually, they size HVAC and piping systems during this initial design. Other trades, such as electrical and fire protection, do not. Therefore, they draw some of the systems to scale and others simply as lines with references to component sizes. The design consultants typically assign full responsibility for coordination to the specialty contractors, including checking for clearances, field conditions, and architectural conditions.

Representatives from each of the specialty contractors (primarily HVAC wet and dry, plumbing, electrical, and fire protection) meet to discuss their particular designs and drawings, which indicate the proposed routing for each system to follow to service each required location. Common constraints for them to consider in routing MEP systems are corridors, openings in shear walls, and architectural requirements, such as ceiling type and interstitial space. The architect and structural engineer set the envelope for routing MEP systems. The preliminary routing drawings reflect these constraints; each trade routes their system to their own advantage. This includes decreasing overall length, routing close to support points, choosing prime locations for major components, and locating system runs to facilitate the construction needs of their own trade.

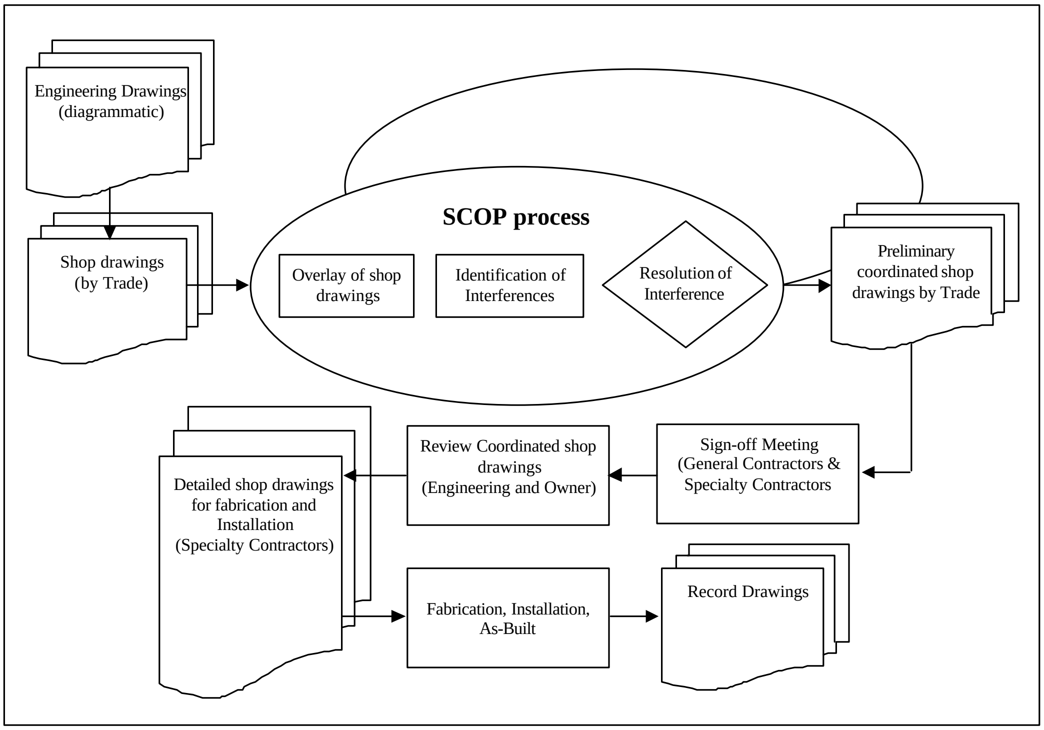


Figure 2.1 - Current practice using light table

During coordination meetings, the participating specialty contractors compare preliminary routing for their systems to identify and resolve conflicts. The MEP trades use SCOP to overlay their design drawings. SCOP continues until they resolve all interferences. This often requires preparing section views for highly congested areas to identify interferences. They also decide which contractor(s) will revise their design and submit requests for information regarding problems that require an engineering resolution. Section 2.5.2 describes this process in more detail. The product of this process is a set of coordinated shop drawings that the specialty contractors submit to the design engineer for approval.

Upon completion of SCOP, all specialty contractors involved (mechanical, electrical, plumbing, and fire protection) sign-off on each others' drawings, indicating that they accept the coordinated design for the specific area of the facility. Specialty contractors then prepare cut sheets for duct fabrication and spool sheets for piping, based on the coordinated shop drawings. They fabricate duct and larger pipe in shops and ship the pieces to the site. The contractors' crews install the systems, using the shop drawings to define location. Quality control personnel generally inspect the system using the diagrammatic drawings from the engineer. To complete the system, the contractors prepare as-built or record drawings by marking and editing the shop drawings or by consolidating electronic files.

2.1.3 Parties involved in MEP coordination

Many firms and individuals are involved in MEP coordination, ranging from specialty contractors to owner representatives. As indicated in Table 2.1, each type of organization sends participants with different backgrounds.

Table 2.1 - Individuals involved in MEP coordination

Organization	Title of personnel
Design consultants	• Design engineers
General contractor	• MEP coordinators • Field superintendents and engineers
Specialty contractors	• Detailers • Engineers • Field foremen
Owner	• Construction managers • Facility managers • Operations and maintenance personnel
Suppliers	• Manufacturing representatives

These individuals each have a different interest in the coordination process. Design consultants act as guardians of the preliminary design to assure that systems satisfy code requirements and will function properly once installed. General contractors focus on the project schedule and on avoiding delays in both pre-construction and installation. Specialty contractors are concerned with the fabrication and installation cost of their specialty system. They try to reduce material, fabrication, and labor cost. The owner tries to make sure the facility materializes on budget, on time, and at the best quality. Suppliers may become involved when the systems include specialized equipment.

2.1.4 Problems with current practice

Many problems exist with the current practice.

(1) The coordination process is slow and expensive. MEP coordination often delays the project and increases the cost for all involved in the process [Hanna 99]. Coordination is often not budgeted in the construction cost. It is a hidden cost in the design category. The sequential and iterative process is very slow because specialty contractors make only slight progress at each meeting. These coordination meetings consume valuable human resources with up to seven people at each meeting. An example of this is the coordination of the MEP systems for labs on the basement floor of the McCullough Annex building on the Stanford University campus. The 57,000-sf basement required 15 meetings and 520 person hours for an estimated coordination cost of $260,000. This estimate includes time spent by personnel inside and outside coordination meetings as well as travel time to meetings.

(2) The coordination process is also highly fragmented. Design and coordination take place on an as-needed basis [Tatum 99]. Engineers and contractors do not perform design and coordination sequentially. There is a lack of knowledge and understanding regarding the multiple disciplines involved, which often gives rise to systems that need redesign to meet coordination criteria. In many instances, parts of the systems must be re-coordinated in different stages.

(3) It is difficult to integrate construction knowledge into the MEP coordination process. Often the parties involved do not take the opportunity to align goals and define requirements [Bergthold 98]. In addition, the MEP design consultants' do not consider constructibility issues, and designers must make assumptions about constructibility or ignore the issue totally. Furthermore, there is a lack of understanding between the different MEP trades. Each discipline focuses on its own design and construction requirements [Sanchez 98]. Failing to consider the big picture, many MEP contractors are unaware of unique installation requirements for other trades and are reluctant to learn more about or consider each other's systems.

(4) Because of the lack of communication between designers, builders, and operations personnel, it is difficult to integrate knowledge about operation and maintenance of the

facility. Operations and maintenance personnel often are not involved in coordination decisions; therefore, designers must make assumptions concerning the user's needs.
(5) Three-dimensional space requirements are difficult to visualize. Currently, contractors perform coordination with two-dimensional flat drawings overlayed on each other. A major problem with this method is the limited interference-checking capability. Specialty contractors need many section views and they manually calculate clearances since they perform the procedure with flat drawings. When specialty contractors produce drawings on computer-aided-design (CAD), they can use a number of software systems products such as QuickPEN™ or AutoCAD's SoftDESK™ for interference checking. Even with the aid of CAD software, specialty contractors may still need to produce cross-section and projection views to visualize congested spaces. In some extreme cases, specialty contractors construct full-scale mock-ups of very congested areas to identify places of conflict in order to alleviate concerns regarding constructibility, operations, and maintenance.

(6) The level of technology used in difficult coordination scenarios varies. Specialty contractors use a wide range of technology to assist with MEP coordination. Plant design systems, which some engineering and construction firms, use on large process and power plants, can avoid many of the problems associated with MEP coordination [Tatum 99]. However, these large projects usually require large computer systems to handle the design on 3D CAD platforms. Specialty contractors, who design, fabricate, and construct the project, perform the MEP coordination on most projects. These specialty contractors usually do not possess the sophisticated computer systems or technical knowledge to take advantage of 3D CAD's capabilities. Instead, they work independently of others, using 2D CAD platforms. In rare cases, a specialty contractor will use a 3D CAD platform for design; however, these are usually very special systems and data are not transferable or compatible with other systems.

(7) Upon the completion of the current coordination process, no electronic models of the facility remain with the owner for use over the facility's life cycle. Facility managers and maintenance personnel use as-built drawings provided by the contractor. Furthermore, the

coordination process often must take place in two stages, once for the coordination of the building systems under the core-and-shell construction contract and again under the construction contract for tenant improvement. Facility managers must prepare as-built drawings of core-and-shell construction in order to provide information for tenant improvement contracts.

2.1.5 Positive aspects of current practice

Despite the many problems with the current practice, some of its positive aspects are as follows:

- it provides opportunity to value-engineer the entire project
- it allows interaction of representatives from many disciplines and construction trades to gather and discuss configuration alternatives
- it promotes sharing knowledge regarding the multiple systems
- it allows for the identification of many problems prior to field work, but it not thorough enough to detect all conflicts
- it instigates discussion of construction scheduling and installation sequencing, but does not allow for a detailed investigation.

In developing the prototype tool as a part of this research, I tried to retain many of these positive aspects (see Sections 8.3 and 8.4).

2.2 Overview of project delivery process for building systems

This section provides a general overview of the process that specialty contractors follow to procure, design, and build work. For MEP coordination, this process is similar for projects using either the design-bid-build or the design-build project delivery methods. Where dissimilarities occur, I note them in the following description. While reading the following section, refer to Figure 2.2 for a summary of the drawings created for building systems during the project delivery process.

The process begins with the owner’s decision to construct a facility and ends with the contractor turning the system over to the owner. It includes the following phases: conceptual design, selection of specialty contractors, award of contract, start of project, engineering, submittal and approval, pre-construction, fabrication, installation, start-up, and turnover. The following sections describe each of these phases.

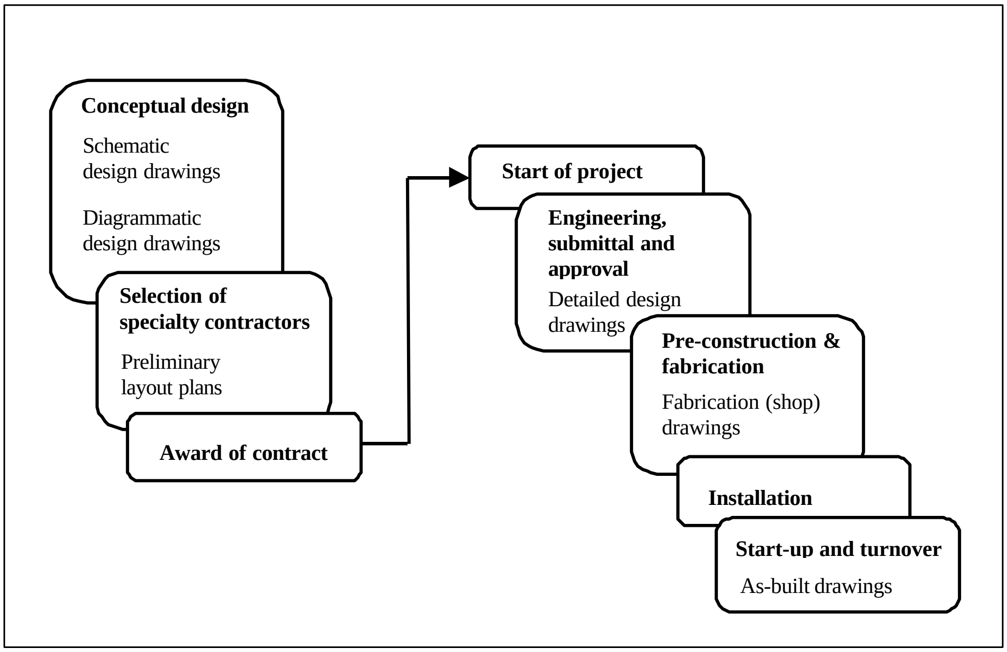


Figure 2.2 - Drawings created for building systems during project delivery process

2.2.1 Conceptual design

In the conceptual design phase, the owner starts with a general idea about the desired type of building. The conceptual design stage usually results in a set of schematic design drawings, which reflect how the architect envisions the building concept. During the initial part of conceptual design, the architect prepares layout sketches with notations about planned use of spaces, approximate square footage, ceiling heights, etc. In this stage of decision-making, the owner determines how the specific spaces in the building will be utilized. Examples of these spaces include offices, laboratories, housing, hospitals, or industrial manufacturing plants. The architect then completes the schematic design drawings to meet the owner's needs.

The final set of schematic design drawings defines the building layout. These drawings generally include elevations, wall layouts, general floor plans, etc. The architect turns the schematic drawings over to multiple engineering design consultants, also referred to as MEP consultants, to design and preliminarily route the building systems. Industry professionals generally refer to the drawings prepared by the MEP consultants as diagrammatic drawings.

2.2.2 Selection of specialty contractors and award of contract

In both the traditional design-bid-build and the design-build project delivery methods, schematic drawings are distributed to pre-qualified specialty contractors for bidding purposes. This is usually the first involvement of the specialty contractor in the project development process. For a design-bid-build contract, a typical package consists of the architect's schematic drawings and the MEP consultants' diagrammatic drawings. A typical package for a design-build contract consists of the architect's schematic drawings and the engineers' design, which consists of user specifications and requirements.

During the bidding period, the specialty contractors' estimators review the drawings and specifications. They prepare a construction estimate for the total costs of building their particular segments of the project (HVAC, electrical, fire protection, etc.). The estimators first begin by preparing preliminary layout plans based on the drawings and specifications or BOD. The preliminary layout usually consists of lines drawn on the architectural floor plan that indicate the route the system eventually will take. This determines the linear footage of a particular system, number of connection points, number of turns, etc. Estimators then price out the material, engineering labor, fabrication cost, field labor, permit fees, and taxes. They then express this total cost as a cost per linear foot. In most specialty contractor organizations, the management team reviews the preliminary estimate and may provide additional input concerning labor, fabrication, and material.

In preparing estimates, most specialty contractors use historical project data to obtain "ballpark" figures. These rough estimates include material, labor, and major equipment. To account for unexpected contingencies, the estimates may contain higher profit margins. To complete a detailed estimate, a contractor must wait for a detailed design.
Once the estimator completes this process, he or she drafts a proposal for the work, along with any necessary clarifications of inclusions and exclusions. The general contractor, architect, and owner then review the proposal in order to identify the lowest cost responsible bidder for the project.

The general contractor awards the bid to the lowest responsible specialty contractor and prepares a contract for the successful bidder to sign. After contract award, the specialty contractor prepares to build the work. These preparations include completing a detailed design, preparing fabrication drawings, and performing mechanical, electrical, plumbing (MEP) coordination with the other specialty contractors prior to construction.

2.2.3 Start of project

At the start of a typical project, the estimator gives all material used to prepare the bid, such as plans and estimates, to the superintendent or foreman who will actually supervise the construction. Specialty contractors typically conduct a pre-design meeting with the engineer, estimator, field foreman, and operations manager. This group reviews the schedule and identifies milestone dates. The review includes examining the estimator's design and layout to identify possible cost savings.

2.2.4 Engineering, submittal and approval

In both the design-bid-build and design-build project delivery methods, the specialty contractors produce the detailed designs. These drawings include actual dimensions and locations of system lines and components. The specialty contractors internally review the design drawings and check them against all code and regulatory requirements. The specialty contractors then begin to coordinate the layout with other trades, including structural, to make sure that all the systems will fit inside the building. (Section 2.3 will provide additional information regarding the engineering design process and Section 2.5 will further describe the MEP coordination phase.)

The specialty contractors then submit detailed design drawings to multiple organizations and request approval for construction. The architect, engineering design consultant, local fire department, and owner's insurance agency typically review and comment on these drawings. If engineers do not approve drawings, the specialty contractor makes corrections and resubmits the drawings.

2.2.5 Pre-construction and fabrication

The specialty contractors' engineering departments list all materials needed for fabrication.

The fabrication department fabricates all necessary components, such as pipes, fittings, hangers, heads, and valves, and prepares them for shipment to the job site. The fabrication manager also typically procures any major equipment that is necessary for the system, such as cooling towers, large pumps, air handlers, exhaust fans, etc. Engineers prepare installation packages for the installation foreman, which include installation drawings, list sheets, and copies of permits. Manufactures and suppliers then ship all materials required for the job to the site for installation.

2.2.6 Installation

During the installation stage, the field superintendent determines the size of crew needed based on the size of the job, the complexity, and the duration between start of installation and turnover of the completed system to the owner. Once the job foreman and crew receive shipment at the site, they distribute the materials to the general location inside the building for installation. Crews then install components in accordance with the drawings.

2.2.7 Start-up and turnover

Upon completion of installation, inspectors test the entire system. The specialty contractors correct discrepancies before the building inspector signs the permits. Finishing contractors complete architecture items such as ceiling, carpeting, and painting before the agencies with jurisdiction issue an occupancy permit.

During this stage, the specialty contractors note any variances between the fabrication drawings and installation of the systems. Industry professionals refer to these marked-up drawings as “As-built drawings.” The owner retains them after completion of the project.

2.3 General criteria that guide the design of building systems

This section summarizes each type of building system by describing its purpose, primary components, and design criteria. It begins by defining the term "MEP systems" and the critical design criteria for these systems, which guide the design process. The overview includes systems for the heating, ventilation, and air conditioning (HVAC), plumbing, process piping, fire protection, electrical, control, and the telephone/datacom.

2.3.1 Definition of building systems

Traditional building systems are parts of the buildings that temper the building environment, distribute energy, allow for communication, enable critical manufacturing process, and provide and dispose of water. Architects and engineers also refer to the building systems as the active systems of the building. Design and construction professionals use the acronym MEP systems, which stands for mechanical, electrical, and plumbing systems. With increases in the functionality and complexity of buildings, projects now include much more than just the traditional mechanical, electrical, and plumbing systems. The MEP scope now includes additional systems such as fire protection, controls, process piping, and telephone/datacom. Although many of these systems may seem similar in nature, different specialty contractors often install them.

2.3.2 HVAC system

HVAC systems heat and cool air and water and distribute these fluids to building spaces to maintain desired conditions. HVAC systems generally include the following components: (1) a heat-generating system, (2) a cooling system, (3) an air-handling system and, (4) a control system for hand adjusting and/or automatic monitoring of the system operation. The HVAC system provides complete conditioning of the air, which also may include filtering out dust and odors, freshening with outdoor air, adjustment of the temperature, and modification of the relative humidity [Tao 01].

The air or “dry” portion of HVAC systems includes fans and ductwork to transport the air from the point of origination to the conditioned space. Fans deliver air to the space through louvers, which ductwork attaches to a mixing boxes or diffusers. The size of the duct depends on its shape (round, flat, oval, or rectangular), the required volume of airflow, and the velocity of the air. The ducts are largest near the fan discharge and decrease in size as air is distributed through individual diffusers or mixing boxes.

Key design considerations for HVAC systems include space for equipment, space for ductwork, properties of the building enclosure, and noise and vibration. HVAC equipment is generally very large and bulky. The equipment must be accessible for maintenance and replacement.

The Uniform Mechanical Code (UMC), specifications prepared by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE), and design standards issued by the Sheet Metal and Air-conditioning Contractors National Association (SMACNA) govern the design for most HVAC systems.

2.3.3 Plumbing system

The plumbing system serves three primary functions – collection and disposal of waste water, distribution of hot and cold water, and collection and disposal of storm water. The piping portion of these systems falls into one of three functional categories: gravity drained waste systems, pumped waste, and pressure-driven systems.

Gravity-drained waste systems require a natural grade to drain waste without pumps. These gravity-drained systems must also have intermittent vent lines along the entire system to allow open channel flow in the drainage network. The pumped waste systems include all waste lines that uses pressure rather than by gravity. All pumped waste systems must run in double contained piping systems. Lastly, the pressure-driven systems include hot and cold water supply lines to the various locations in the building.

The Uniform Plumbing Code (UPC) governs the design of most plumbing systems. Local jurisdictions may impose additional design requirements beyond the UPC.

2.3.4 Process piping system

Process piping systems supply gas or liquid to laboratories, hospitals, and manufacturing facilities. These systems commonly include oxygen, nitrogen, compressed dry air, deionized water, water for injection (for pharmaceutical plants), and vacuum lines.

Process piping systems use a variety of materials due to the purity requirements for many of the systems. These include stainless steel tubing, Polyvinyldenefluoride (PVDF), plastic duct, and Polyvinylchloride (PVC) piping. These systems are mainly pressure-driven and may require double-contained piping due to the nature of the fluids that the piping transports.

The Uniform Fire Code (UFC) - Article 80, the UPC, local Toxic Gas Ordinances (TGO), and American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Codes govern the materials, design, installation, and testing of these systems.

2.3.5 Fire protection system

The two primary objectives of the fire-protection system are to save lives and protect property. The design approach is to make the building fire resistant and to facilitate the speedy evacuation of occupants in case of a fire. Contrary to popular belief, this system can only retard fires during extreme emergencies.

Fire protection systems components consist of vertical stand pipes, horizontal main lines, and branch lines, which run in the ceiling space of the building. These pipes, along with sprinklers, distribute water in case of a fire. Fire protection systems fall into one of four categories: wet, dry, pre-action, and deluge. In wet systems, water is always under pressure in all pipes and mains. In dry systems, pipes contain compressed air or nitrogen until the opening of a sprinkler permits water flow. Pre-action systems are similar to dry systems, except that valves release water to the pipes before any sprinkler head has opened. In a deluge system, the sprinklers are open and all go off at once [Stein 86].

The design parameters for these lines are set in accordance with NFPA-13 (National Fire Protection Association); however, these are only minimum requirements. Fire-protection systems designers must also contact local jurisdiction officials and the owner’s insurance rating agency (e.g., Factory Mutual, Industrial Risk Insurer) for requirements beyond the minimum standard.

2.3.6 Electrical system

Electrical systems are an integral part of the overall building design process. The electrical system carries electric current from a utility source to electrical loads that are located throughout the building. These include lighting systems, electrical equipment, vertical transportation systems, and other building mechanical systems. With the increase in communication devices (computers, fax machines, etc.), the demand for electrical power in buildings has increased drastically in recent years.

Electrical systems do not require much building space compared to mechanical systems; however, the architecture permits exposure of electrical equipment in occupied areas. Its location, configuration, and aesthetics must be coordinated with architectural design [Tao 97]. The major categories of the electrical system are supply, distribution, and lighting. Common components for electrical supply are transformers, panel boards, and motor control centers. Portions of these systems delivering power are conduits, cable trays, and electrical bus bars.

The National Electric Code (NEC) sets the design parameters for electrical systems. Electrical designers and specialty contractors must meet these requirements. Electrical system designers must also adhere to NFPA 13 and the governing building code, such as the Uniform Building Code (UBC) or International Building Code (IBC), for requirements beyond the minimum set forth by the NEC.

2.3.7 Control system

The primary purpose of control systems is to provide a stable or programmed operation of a process in a plant or a building by maintaining desired values of variable conditions, such as pressure, temperature, flow, force, and liquid level. One example of how control systems are used is to control HVAC systems. Control systems for HVAC systems regulate the performance of the equipment to maintain desired environmental conditions.

Control systems are generally either pneumatic or electronic. A pneumatically controlled system uses air distributed in copper or plastic tubing to distribute pneumatic signals. An electronic system uses electrical current in twisted shielded pair (often 18 AWG) wiring to control components and devices. Control engineers always begin designing control systems last because mechanical and electrical engineers must define all mechanical and electrical devices first. Control contractors usually begin installing these systems last because the other trades consider the most flexible in routing due to their small diameter tubing and conduits. These systems typically use other trades' support mechanisms.

2.3.8 Telephone/datacom system

In recent years, telephone/datacom systems have become more complex and more important in buildings as work locations become communication hubs. Telephone communications systems are composed of copper communication lines, while data communications systems use fiber optic lines, both of which extend throughout the facility. The building volume that these systems use is growing and they often require a dedicated raceway.

The above summary indicates that building systems must satisfy many types of design criteria from many sources. Table 2.2 summarizes the codes and standards governing the design of building systems.

2.4 Role and need for coordination of building systems in the design process

The need for MEP coordination grows out of the lack of detailed design for fabrication and installation of building systems regardless of the project delivery process. This section describes MEP coordination in the context of both the design-build and the design-bid-build project delivery methods. It describes what creates the need for the MEP coordination process in both of these project delivery approaches.

Table 2.2 – Codes and standards governing the design of building systems

System	Organization or Code

HVAC	• Uniform Mechanical Code (UMC) • Uniform Building Code (UBC) • Building Officials Code Association (BOCA) • Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) • American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHREA)
Plumbing	• Uniform Plumbing Code (UPC) • Uniform Building Code (UBC) • Building Officials Construction Association (BOCA)
Process piping	• Local Toxic Gas Ordinances (TGO) • Uniform Fire Code (UFC) - Article 80 • American Society of Mechanical Engineers (ASME) - Boiler Code • American Society of Mechanical Engineers (ASME) - Pressure Vessel Code
Fire protection	• City fire marshals • Uniform Fire Code (UFC) • City Ordinances • National Fire Protection Association– Article 13 • Uniform Building Code (UBC) • Building Officials Construction Association (BOCA)
Electrical	• National Electric Code (NEC) • Uniform Building Code (UBC) • Building Officials Construction Association (BOCA) • National Electrical Manufactures Association (NEMA) • National Fire Protection Association (NFPA) – Article 13
Control	• Control device manufactures • National Electric Code (NEC) • Uniform Plumbing Code (UPC) • International Society for Measurement and Control (ISA)
Telephone/data communications	• Local communications company

2.4.1 Need for coordination under design-bid-build contracts

The need for MEP coordination in the traditional design-bid-build scenario grows out of the nature of the contracts between the architect, design consultant, general contractor, and specialty contractors. In the traditional design-bid-build scenario, the architect has control of the building envelope. The architect designs the structure to meet the needs of the owner. These needs determine the space and shape of the structure as well as the aesthetic aspects of the building.

The architect then engages an engineering design consultant to design the MEP systems, which include HVAC dry, HVAC wet, plumbing (gravity-driven systems), plumbing (pressure-driven systems), electrical, and telephone/datacom. In high-tech facilities, this list also includes process piping. The specialty contractors are not involved in the design of the systems. Their role is to detail, fabricate, and install the system.

The engineering design consultant performs a detailed analysis and prepares design calculations for each of the systems. These include sizing each system component. Engineers convey this information to the specialty contractors by the contract drawings or design drawings. The design consultant reference these drawings by the particular trade or discipline that installs them, i.e., mechanical design drawings, electrical design drawings, plumbing design drawings, etc. I describe the level of detail shown on these drawings below.

Most specialty contractors refer to the contract drawings as schematic design drawings. The stamp that the engineer provides only insures that the design of the systems will work functionally. In this scenario, the design consultant remains the engineer of record (EOR) and retains liability for the system; however, these drawings are not detailed enough to either fabricate components or construct the systems. The required size of components, such as conductor wire, duct dimensions, and pipe diameter are called out on the drawings, but no scaling of the components is shown in the drawings. Table 2.3 lists the level of detail shown on the drawings.

Table 2.3 - Level of detail shown on schematic drawings for various MEP systems

System	Level of Detail
Mechanical (HVAC dry)	Drawings show major equipment and duct lines, including duct size, but excluding insulation, exact dimensions, and location of major equipment.
Mechanical (HVAC wet)	Drawings show major piping lines and number of connection points into VAV boxes, but do not include size or material type.
Electrical	Drawings show outlet locations and some main electrical lines, but no electrical runs.
Plumbing	Drawings show plumbing lines, indicated only by single lines and pipe size, as well as offset from wall, insulation, and material type.
Process piping	Drawings show rough location of branch piping, indicated by single lines, offsets from walls, but not the insulation or material type.
Fire protection	Drawings show the preliminary layout of sprinkler heads, but the specialty contractor must determine exact locations. Plans do not show loops or circuits.
Telephone/data communications	Drawings show the outlet locations, but not the loops or circuits.

It is the specialty contractor's responsibility to build the particular building system from these design documents. This requires that the contractor produce shop drawings, also known as fabrication drawings. The shop drawings include the detailed information required by the specialty contractor to fabricate and install a particular building system. The information shown on these drawings, as summarized in Table 2.4, includes joint type, member size, material type, connection mechanism, top elevation, bottom elevation, supply contents, and exact location references.

Specification requirements typically found in design-bid-build contracts state that it is the specialty contractor's responsibility to field coordinate the multiple building systems between the trades. Therefore, once specialty contractors have produced the shop drawings, the coordination process begins. During MEP coordination, all the specialty contractors meet to determine the exact location of each system. They compare each system with each other system, identify interferences and conflicts, and decide how to resolve them.

Table 2.4 – Level of detail shown on shop drawings for various systems

System	Level of Detail
Mechanical (HVAC dry)	Drawings show all major equipment and duct lines, including exact size and location. The duct sizes typically do not include insulation.
Mechanical (HVAC wet)	Drawings show major piping lines and number of connection points into VAV boxes, including size and material and all joints and connection points.
Electrical	Drawings show all outlet locations, all main electrical lines, but not the exact location of circuit lines.
Plumbing	Drawings show plumbing lines, indicated by single lines on drawing. Call-outs indicate wall-offsets, insulation and material type on the drawing, as well as all joints and connection points.
Process piping	Drawings show dimensioned outlet and drop locations as well as piping lines. Single lines represent piping on drawing. Call-outs refer to the pipe material type, size, offsets from wall, and insulation type and thickness.
Fire protection	Drawings show all sprinkler locations. Reflected ceiling plans indicate the location of all sprinkler heads. Also shown on drawings are all loops, circuits, joints and connection points.
Telephone/datacom	Drawings show all outlet locations, but do not include loops or circuits.

2.4.2 Need for coordination under design-build contracts

In the design-build project delivery method, architects still function as the prime design consultants. Architects are responsible for how occupants will use the space in the building, a direct result of the owners' needs and requirements. In a design-build contract, the architect employs an engineering design consultant, just as in design-bid-build; however, a key difference between the two project delivery methods is the function that the engineering design consultant serves.

In the design-build approach, the engineering design consultant prepares specifications regarding the various MEP systems. The specifications, usually called Basis of Design (BOD), define the performance characteristics that each individual system must meet. For example, the engineering design consultant recommends the required airflow to a particular room or power requirements for a part of the building. They do not prepare conceptual drawings or complete design calculations. The main role of the engineering design consultant is to help the architect prepare specifications. They make preliminary calculations to determine service loads in particular rooms, based on user needs. They do not size or route any of the systems.

For the MEP systems, the contract drawings include only a layout of the building by the architect. Using the design specifications and the building layout drawings, the specialty contractor prepares a detailed design for the system. The specifications include requirements for facilities, equipment, and performance criteria for the overall systems. The engineering design consultant prepares performance-based specifications, meaning that the final design must meet the criteria set forth by the architect. The architect gives the specifications in combination with the schematic design drawings to the specialty contractor as the basis for routing the system and completing the detailed design.

The contract requires that the specialty contractors completely design all systems. The specialty contractors then become the engineers of record (EOR) and assume the design liability for their systems. Therefore, under the design-build approach, the specialty contractors are responsible for the design, routing, and coordination of the building system. The engineering design consultants serve as reviewers of the final design to ensure that it meets the specifications and the owners' requirements.

2.4.3 Contract requirements for MEP coordination

In both the design-bid-build and the design-build project delivery methods, the contract typically indicates that the documents provided to the contractors only show the general arrangement of equipment and accessories located inside the building. The contract requires the contractor to work with the other specialty contractors to identify and resolve interferences that may affect their work.

The examples of contract language shown below come from both design-build and design-bid-build contracts:

> *The general contractor shall coordinate all equipment and accessories with all the trades and shall furnish any information necessary to permit installation with least possible interference or delay*. [PDL 98]
>
> *It is the responsibility of the Heating and Ventilating Contractor to coordinate the work with the Plumbing Contractor and Electrical Contractor and other subcontractors.* [Lam 95]
>
> *The contractor shall cooperate with the other subcontractors in order to establish the responsibilities of each so that work can be completed without delay or interference.* [Alza 97]
>
> *The contract documents show the general arrangement of equipment, ductwork, piping, and accessories. Provide offsets, fittings, and accessories, which may be required but not shown on drawings. Investigate the site and review drawings of other trades to determine conditions affecting the work and provide such work and accessories as may be required to accommodate such conditions.* [Stanford 96]

2.4.4 Summary of the need for MEP coordination

As described in the above sections, architects generally focus on form, space, finishes, and other features that determine the appearance and function of the building. The need for MEP coordination grows out of the fact that designers do not provide detailed designs for fabrication and installation of building systems. Therefore, MEP coordination is necessary regardless of the project delivery process used.

2.5 MEP coordination process

This section provides a detailed description of sequential comparison overlay process (SCOP) and ends with a summary of factors that indicate good results of the process.

2.5.1 Overview of process

The coordination process takes place in a series of meetings in which representatives from each of the specialty contractors bring together their preliminary drawings to resolve coordination problems. At coordination meetings, the underlying goals of the group are to

meet code requirements, insure that the systems function to meet user needs, verify that the systems are feasible to install, and maintain an economical routing and design.

The preliminary shop drawings that each specialty contractor brings to the meeting indicate the path preferred for each branch of the system to reach the required locations and perform essential functions. Architectural, structural, and diagrammatic drawings constrain this routing. Within these constraints, electrical contractors route systems based on the lowest cost. However, it generally does not consider the other systems.

The representatives then sequentially compare their transparent drawings using a table with a light installed below a glass surface. They prepare section views for highly congested areas, identify interferences, and decide which contractor(s) will revise their design(s). The SCOP process continues until they resolve all interferences. The product of this process is a set of coordinated shop drawings submitted to the engineer for approval. The following section describes the details of this process.

2.5.2 Detailed description of the Sequential Comparison Overlay Process

SCOP is an iterative process of sequentially overlaying multiple drawings of various trades. Figure 2.3 graphically represents the SCOP; it follows the priority given in Table 2.5.

To begin SCOP, the specialty contractor lays down a transparent drawing of the HVAC dry system on the light table for comparison with all other shop drawings. The drawing displays the preliminary routing for the system. Specialty contractors commonly use the HVAC dry system as a base because it has the largest components, primarily composed of large ductwork and variable-air-volume (VAV) boxes. They are hardest to relocate. Large duct sizes restrict the routing to a few locations where adequate space is available.

The HVAC wet (hot and cold-water) system is the first system to overlay the HVAC dry system because it directly feeds into the HVAC dry system. The HVAC dry and HVAC wet systems work together and must be tightly coordinated. Routing of the HVAC wet system is based on the HVAC dry system routing and location.

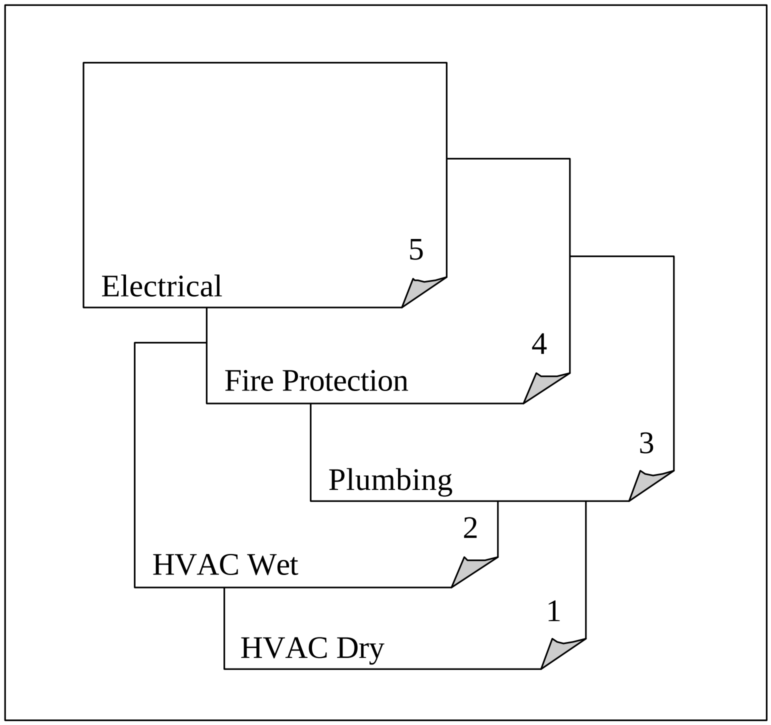


Figure 2.3 – Sequence for comparison overlay process

Next, the plumbing system, including all graded lines, waste lines, and vent lines, enters into the coordination process. The requirement to slope all graded lines and waste lines to allow for gravity flow gives the plumbing system the next highest level of priority after the HVAC dry system. The gravity drain lines typically slope 1/8 inch for every foot. This requirement forces the drain lines to compete with the large HVAC dry ducts at the higher elevations because they must start as high as possible to maintain the grade without falling below the ceiling tiles. Engineers route HVAC dry ducts at higher elevations because of their large volume.

Where process piping is included as a building system, it is coordinated following the plumbing system. Most process piping systems are pressure-driven and thus can yield to larger building system components and gravity-driven system lines that are more difficult to re-route due to the risk of affecting their functionality. In cases where a special routing is required for process piping to function at its optimal performance level, engineers assign priority to the process-piping system.

Table 2.5 - Priority order for sequential comparison process

System	Priority/special notes
Mechanical (HVAC Dry)	Usually first due to large size of components
Mechanical (HVAC Wet)	Follows HVAC Dry due to interdependence of these systems
Plumbing (gravity driven systems)	Design criteria for slope essential for system performance
Process piping	Takes first priority if critical to manufacturing process
Fire Protection	Most flexible routing, especially small diameter pipe
Plumbing (pressure driven systems)	Lower priority because less difficult to re-route
Electrical	Flexible routing within safety and architectural requirements
Control systems	Flexible routing but must limit bend radius for pneumatic tubes
Telephone/Data communications	Flexible routing but must limit bend radius for fiber optic cables

Next in the coordination process is fire protection. This is a pressure-driven system; however, the fire protection main lines must be slightly graded to allow scheduled draining as required by operations and maintenance. This complicates the coordination of the main lines. Engineers and contractors compare drawings individually with HVAC dry, HVAC wet, and plumbing systems.

Consideration of the electrical system follows the fire protection system. Engineers consider the electrical system to be one of the more flexible systems because the components are generally smaller and installers can be easily route electrical conduit in the field. However, this is only true for branch conduits which are 1/2-inch diameter and smaller. Larger electrical main conduits receive priority. This is because the greater the number of elbows and bends, the more difficult it becomes to pull cable.

Contractors coordinate the control systems and telephone/datacom systems last. The control system is the most flexible because of its smaller diameter tubing and conductors. Components in the control system run along other systems, such as HVAC dry and process piping. Therefore, specialty contractors usually coordinate the control system in the field. The primary problem with the telephone/datacom systems is routing these lines adjacent to electrical distribution cables. Engineers usually avoided this problem by segregating telephone/datacom lines from transmission lines by at least three feet.

There are many places in facilities that repeatedly cause coordination problems. These include building corridors, points of entry and exit, openings in shear walls, and vertical chases. Table 2.6 lists some of the more typical coordination problems I found in these areas by observing coordination meetings and by interviews with MEP coordination experts. The table also list options coordination experts use for avoidance or resolution.

2.5.3 Indicators of Good Coordination Efforts

As a part of researching the current process for MEP coordination. I also sought to identify what industry professionals deemed to be indicators of good coordination. I felt that by incorporating these points, I could measure the effectiveness of the knowledge framework and reasoning structure developed in my research.

Table 2.7 lists the indicators for evaluating the quality of the MEP coordination effort classified by project phase. Industry professionals consider coordinated building systems with these characteristics to be well-coordinated projects.

Table 2.6 - Typical problems encountered during coordination

Coordination issue	Ways to avoid or resolve
Graded plumbing lines interfering with ductwork	• Drop ceiling grid • Move one component to side • Penetrate ductwork • Flatten ductwork • Drop ductwork below plumbing line • Split ductwork around plumbing line
Graded plumbing line interfering with structural member	• Cope structural member • Penetrate structural member
Components interfering with access space for valves	• Move components away from valve
Ductwork interfering with lighting fixture removal clearance space	• Drop ceiling grid • Move ductwork away from lighting • Flatten ductwork
Vertical space not adequate to place all components	• Drop ceiling grid • Place electrical conduit in floor slab • Use alternative ductwork shape
As ductwork drops below structural element, bottom of ductwork falls below ceiling grid	• Drop ceiling grid • Flatten ductwork • Penetrate structural member
Components too close to structural system, therefore not allowing proper area for fire proofing	• Move components down to allow for proper thickness of fire proofing
No access space for maintenance	• Move components to sides to create access area
Component support systems interfere with other components	• Create common support systems for all systems

Table 2.7 – Indicators for evaluating the quality of MEP coordination efforts

Project Phase	Indicator
Design	• minimize number of fittings and connections • group and centralize similar systems • group similar systems at same elevation • route systems on grid pattern, perpendicular to building walls • minimize the number of diagonal lines
Construction	• decrease cost for installing components • decrease schedules for installing systems • maximize number of prefabricated components • minimize level of rework in the field • consider installation sequence
Operations and Maintenance	• provide adequate access space for operations and maintenance • reserve adequate space for future expansion

2.6 Summary

MEP Coordination is the arrangement of components of various building systems within the constraints of architecture and structure. Not only must designers arrange the building systems physically, but also they must meet performance expectations for comfort and safety. This process has become a major challenge for projects. The need for MEP coordination grows out of the lack of detailed design provided for fabrication and installation of building systems, and exists regardless of the project delivery process used. The current practice has three primary problems: the process is fragmented, the level of technology used varies greatly, and engineers and contractors rarely create facility models upon completion of the process.

Now performed manually, MEP coordination requires considerable time from scarce experts who have specialized knowledge about the design, construction, operation, and maintenance of these systems. This research can assist in the MEP coordination process by integrating knowledge with 3D CAD. This research used knowledge integration and object representation to integrate design, construction, operations, and maintenance knowledge in a format that is useable by a reasoning structure to assist in solving coordination problems. However, before describing the research, I will review other research related to MEP coordination, knowledge integration, and developing computer tools, so that I can build upon it. Chapter 3 summarizes the relevant past research and defines a point of departure for this thesis.

Chapter 3 – Review of Related Research and Point of Departure

The primary focus of this research is to improve coordination of mechanical, electrical, and plumbing systems, which are the active systems of a building. This chapter summarizes relevant background for this research. The key topics in this point of departure are integrating multiple products over their respective life cycles, using knowledge frameworks and reasoning structures to approach similar problems, and developing computer tools. Reviewing the background and establishing the point of departure for these three topics is necessary to highlight the additions to knowledge needed in these areas to meet the objectives of this research.

3.1 Background for Determining Related Research

As defined in Chapter 2, MEP coordination is the arrangement of components of various building systems within the constraints of architecture and structure. Not only must designers locate and route building systems, but they must design the systems to meet performance expectations for comfort and safety. The need for MEP coordination grows out of the lack of detailed design provided for fabrication and installation of building systems, and is necessary regardless of the chosen project delivery process. This format proved effective for this research because MEP coordination activities, and the knowledge this process requires, are structured by discrete objects.

The current manual means of performing MEP coordination require considerable time from scarce experts who have specialized knowledge about the design, construction, operation, and maintenance of these systems. The results of this research can assist in the MEP coordination process by integrating knowledge with the 3D CAD model of the facility. This research used object representation to demonstrate how to integrate design, construction, operations, and maintenance knowledge in a format that is useable by a reasoning structure to assist in solving coordination problems.

Before conducting this research, I felt the need to investigate other industries that require multi-discipline coordination efforts, use knowledge frameworks and reasoning structures to solve similar problems, and apply current computer technology and research results. The research I explored in this chapter served as useful background for this thesis. However, as I will describe below, the limitations of this background preclude direct application for coordinating MEP systems in buildings for two reasons: multi-discipline coordination and knowledge intensity. In this research, I laid the foundation for developing a knowledge framework and reasoning structure that is able to include many disciplines, while integrating a vast knowledge base to perform configurational tasks necessary for MEP coordination.

3.2 Integration of multiple products over their life-cycles

Building systems serve independent functions but have spatial and functional links to each other; therefore, MEP coordination is essentially a problem of integrating multiple products over their life cycles. In order to comprehend this, an understanding of the life cycle of each product is necessary. Figure 3.1 shows the stages of a typical product life cycle, starting with its conceptual design to its disposal and recycling [Prinz 91].

In the product life cycle, there are two key information flows: synthesis, which focuses on downward information flow and exploration of alternatives, and abstraction, which allows constraints from later stages, such as performance and constructibility, to be accessible during earlier stages where they may have an influence. Configurational design is the stage in which engineers make spatial arrangements and adjustments. Therefore, MEP coordination is the "collective" configurational design stage for all building systems.

To design systems that comply with the indicators of good coordination (see Section 2.5.3), engineers require knowledge from upstream and downstream stages in the product life cycle. The synthesis mechanism creates options for multiple spatial arrangements and places constraints on these options. Chapter 6 will further explain this.

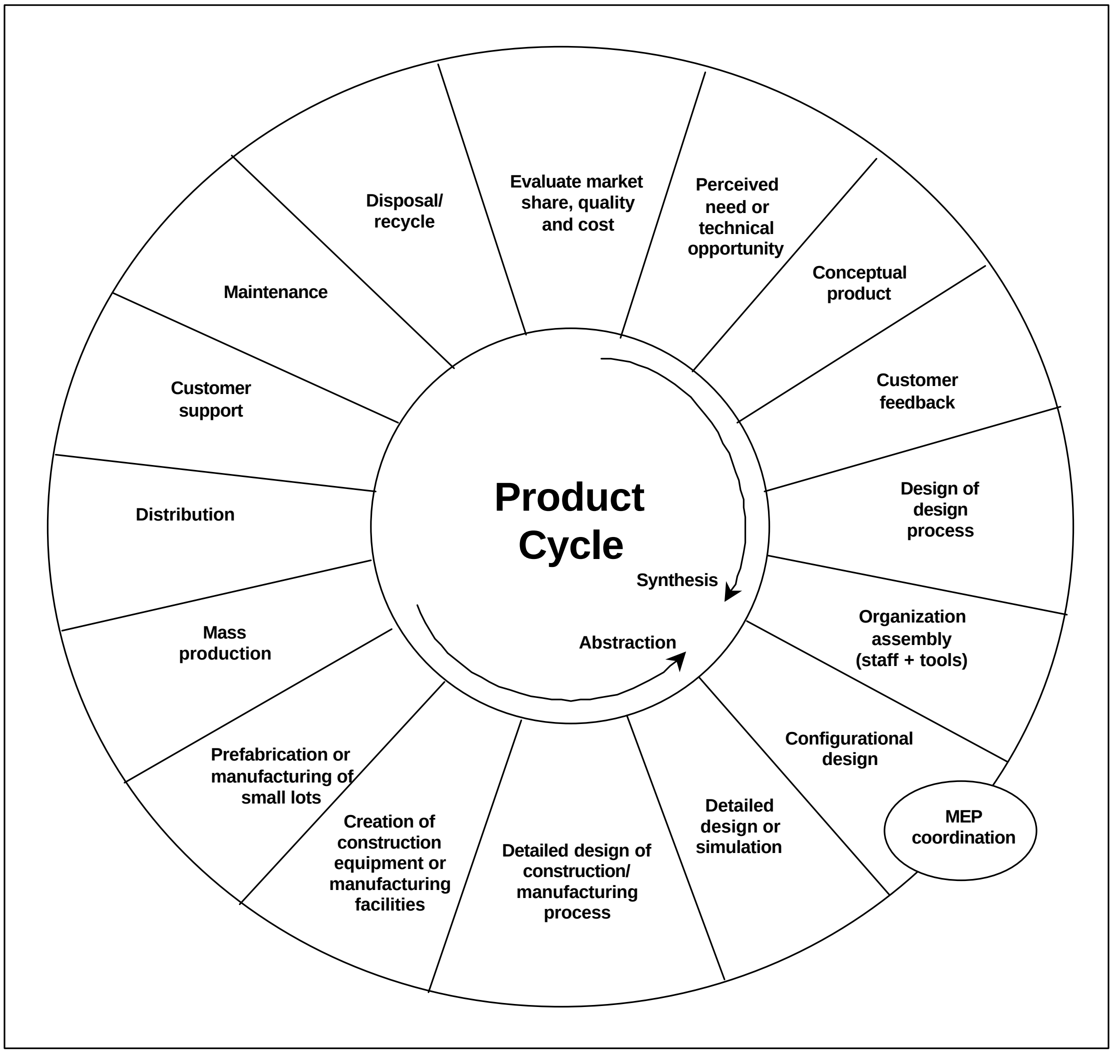


Figure 3.1 - Tasks related to the product cycle

3.2.1 Facility design and construction

I reviewed current literature and industry data such as company manuals. These contained no detailed background regarding the integration of mechanical, electrical, and plumbing systems. Therefore, the first objective of this research was to describe current practice. The background for MEP coordination in Chapter 2 included an overview of the project delivery process for building systems, a summary of the general criteria that guides the design of building systems, and a description of the current practice for MEP coordination.

3.2.2 Product design and manufacturing

The equivalent of MEP coordination in the product design and manufacturing industry is required for ships, aircraft, and automobiles, which require coordination of multiple active systems located within their structure. Table 3.1 summarizes the coordination technique used for each type of product.

For aircraft and ships, the most common procedure for coordinating mechanical, electrical, and plumbing systems is to designate pathways for each system during the design of the product. Engineers then route the systems within these reserved spaces to required locations and show them on drawings. Overlays and section cuts show the coordination of the systems. The slow and expensive process previously required a full-scale model of the aircraft to identify interferences. Once engineers determine an optimal arrangement, engineers repeat results exactly for each product produced.

This process changed dramatically with the design and manufacture of the Boeing 777 airplane. Engineers used the CATIA™ design software to design and route all systems on board the aircraft in a 3D model. This enabled Boeing to complete a virtual design without building a full-scale mock-up of the aircraft [Dornheim 91].

For automobiles, specifically engine design, a process known as incremental design entails never starting with a new design. It always uses an existing design as a basis for the new design and makes incremental adjustments. The automobile industry is very quick to move to the detailed design stage by choosing to produce prototypes rather than by producing configurational design drawings. By investigating system coordination in each of these products, I gained a broader understanding of the coordination process.

Coordination of the active systems takes place in products other than buildings. Investigating these products influenced my development of the knowledge framework and reasoning structure. I specifically incorporated the maintenance aspects of these products into my knowledge framework for building systems.

Table 3.1 – Coordination of active systems in various types of products

Structure	Coordination technique

Ships	Overlay of translucent drawings with section views.
Aircraft	Virtual 3D product model in CATIA design software.
Automobiles	Incremental design and full-scale 3D-product model.

3.3 Knowledge frameworks and reasoning structures

Knowledge frameworks capture the essential characteristics needed by knowledge-based systems. Combined with reasoning structures or logic, they provide an integrated knowledge representation [Parsaye 88]. Such frameworks represent knowledge in a number of applications, such as the following examples for facility design and construction, and product design and manufacturing.

3.3.1 Facility design and construction

Most knowledge-based systems focus on one particular phase of the design or construction cycle. The following examples demonstrate how knowledge frameworks and reasoning structures have integrated knowledge to assist designers in a particular task.

Fischer developed COKE (COonstruction Knowledge Expert), which identified design-relevant constructibility knowledge to help concrete structure designers check for constructibility issues during the initial configurational design task. In his research he acquired and organized a large constructibility knowledge base for formwork systems suitable for the design of reinforced concrete structures. The primary solution classes used in this research focused on the constructibility issues regarding specific structural elements – beams, slabs, columns, and walls [Fischer 97]. COKE differs from this MEP research in that it focused specifically on constructibility issues in the preliminary design phase, whereas the research described in this thesis integrates design, construction, operations, and maintenance issues during the coordination phase. Thus, the two projects differ in type of knowledge and phase or type of design.

Tommelein's SightPlan tool employed a knowledge framework and reasoning structure to assist construction managers in configuring temporary facilities on construction sites. The knowledge framework, which included knowledge about site layout, focused on two main space adjacencies: *In-zone* and *Adjacent to*. These adjacencies served as constraints for layout decision-making [Tommelein 92]. This knowledge focused on the construction phase and reasoning regarding physical spaces in 2-D planes.

Chinowsky developed CADDIE, a knowledge framework used to assist in configuring the building layout for architectural plans [Chinowsky 91]. The framework included design layout knowledge to help architects develop conceptual design diagrams. It focused on a limited number of domains and spatial adjacencies: space planning, acoustics, security, privacy, and daylighting. CADDIE focused on the conceptual design stage. Its knowledge addressed the layout of a single building type (university research buildings) and considered 2-D reasoning and single-story layout.

Prior research to develop knowledge-based systems for detailed design of construction processes include Aalami's Construction Method Modeler (CMM) tool and Riley's work on space planning for the sequencing of mechanical, electrical, plumbing and fire-protection trades. Aalami's CMM tool seeks a preferable work method for a particular structural design [Aalami 98], while Riley's work tries to avoid or minimize schedule losses due to spatial conflicts during installation of components [Riley 97]. Since they seek to assist in designing a detailed construction process, both knowledge-based systems used a construction schedule to reduce the number of conflicts during field construction delays.

3.3.2 Product design and manufacturing

A number of knowledge frameworks and reasoning structures assist in product design and manufacturing. One of the most notable knowledge frameworks, Magic^{TM}, was developed for a Very Large Scale Integration (VLSI). Magic^{TM} is a sophisticated configuration-layout system for integrated circuits that brings manufacturing knowledge into the design process. It 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 84].

3.4 Computer Tools

In facility design and construction as well as product design and manufacturing, designers use computer tools to automate specific design tasks related to the product cycle. Most of these computer tools have focused on detailed design/simulation tasks related to the product cycle. However, more recent computer tools have been able to assist with additional tasks related to the product cycle (see Figure 3.1). These tasks include detailed design to determine a preferable work method and sequence and configurational design to identify an optimal arrangement of objects.

To pursue each new capability, researchers have employed knowledge-systems software technology that allows knowledge integration with computer representations of facilities or products. This software uses a knowledge framework and reasoning structure to link an object (component) with a particular set of knowledge. The following examples illustrate attempts to integrate knowledge with geometric models and bridge the gap between design tools and geometric models using knowledge-based systems.

3.4.1 Facility design and construction

Traditionally, construction has lagged behind other industries in the use of computers. In recent years, 3D CAD models have become more popular in the design and construction industry. These tools are able to produce a complete product model, which assists in the configurational design task. Currently, there are many software products related to the design of MEP systems. Tables 3.2 through Table 3.4 categorize the major commercial tools by their primary application in the product cycle.

These tools allow for faster design in detail, as they contain libraries of components stored in databases for use in building a specific plant model. However, these current commercial tools do not allow full integration of building systems nor are they able to use knowledge frameworks and reasoning structures to assist in the configurational design task. Many of the tools have the ability to detect both physical interferences and clearance violations. However, they rely on knowledge from coordination teams and do not provide feedback.

Table 3.2 – Commercial tools for detailed design/simulation task

Tool name	Capabilities
SPIPE – Plumbing design software (Elite Software Development, Inc.)	Computes optimal pipe sizes for hot and cold-water domestic water supply. Capabilities include system performance calculations, automated generation of bill of materials, and labor estimates.
FIRE – Fire sprinkler design software (Elite Software Development, Inc.)	Performs all necessary hydraulic calculations as required by the NFPA 13; capabilities include estimating sprinkler head requirements and calculating optimal pipe sizes.
Ductsize – Duct design software (Elite Software Development, Inc.)	Calculates optimal air conditioning duct sizes for round, rectangular, and flat oval ducts, including total duct section surface area and weight based on design procedures.

Table 3.3 – Commercial tools for configurational task

Tool name	Capabilities
Softdesk – Building Services Edition (Autodesk Corp.)	AutoCAD™-based design tool for mechanical, electrical, and piping systems. Capabilities include automatic generation of schedules and bill of materials as well as interference detection.
3DM – Bechtel 3D System (Bechtel Corp.)	3D computer modeling system that includes capabilities for interference detection, drawing creation, generation of bill of materials, and model verification. Also provides capability to design and model mechanical, electrical, and piping systems interactively.
SolidBuilder (EaglePoint Software)	Residential and light construction application that creates the 3D model and automatically frames using wood, logs, steel, concrete, brick/block. Capabilities include automated cutting and layout lists, bill of materials, and quantity takeoff.
PlantSpace (Bentley Systems, Inc.)	3D modeling software for mechanical, electrical, and piping. Provides for interactive specification-driven design process for process and power plants. Capabilities include detection of both physical clashes and clearance violations.
CCPlant – Plant Design Software (Silicon Graphics, Inc.)	Fully integrated, object-oriented, rule-based modeling software, covering piping, equipment, structural, and ductwork. Allows for concurrent design including interference detection, layout verification, and standards compliance.
ArchT (Ketiv Technologies, Inc.)	AutoCAD™-based object-oriented software that aids in the automating the design of building components that includes component databases containing specified properties.

3D models also allow for increased visualization of design. Drafters represent all components and objects visually. Individuals are able to visualize rather than conceptualize difficult geometric configurations [Hill 98]. Visualization helps with some coordination issues; however, the benefits from visualization techniques are limited by the knowledge of those looking at the model. For example, extremely congested areas are difficult to visualize. It is often difficult to determine clearances between components and project teams require many projections and sections to identify interferences.

Table 3.4 – Commercial tools for both detailed design/simulation and configurational tasks

Tool name	Capabilities
QuickPen (QuickPen Intl.)	3D sheet metal and mechanical system design software, which assists in HVAC dry layout. Capabilities include automatic collision checking, automated generation of 3D spools, data transmission to plasma cutters for fabrication, and automated generation of bill of materials.
AutoPLANT (Rebis – Industrial Workgroup Software)	AutoCAD™-based, object-based, 3D piping module that assists in design and modeling of piping networks. Capabilities include automated isometric generation program, including automatic dimensioning, annotation, and bill of materials.
CATIA™ (IBM)	CATIA™ Version 5 allows users to capture and reuse corporate expertise throughout the product life cycle. Combines the power of explicit rules that define the product behavior, with interactive capture of design intent as the design is built. The system acts as an expert advisor to guide you through the task, warning you of rule violations and conflicts.
AutoRouter (DesignPower, Inc.)	Algorithmic optimization routing software for process and chemical plants. Routes pipes direct from P&ID to 3D piping. Capabilities include automated nozzle placement and automated generation of CAD drawings.

An example of a knowledge-based tool developed to assist in configurational task is Fischer's COKE, which helped to bridge the gap between design and construction. COKE identified design-relevant constructibility knowledge to help concrete designers check for constructibility issues. The tool successfully integrated construction knowledge into the early phases of design using a number of heuristics regarding application, layout, dimensioning, detailing, and exogenous factors. It achieved this by providing a designer of reinforced concrete building structures with constructibility feedback related to the layout and dimensioning of the structural elements [Fischer 96a]. COKE focused on conceptual design by one discipline and has no visualization capability.

3.4.2 Product design and manufacturing

In the product design and manufacturing sector, computer tools have focused on one particular aspect of design and manufacturing. Traditionally, the purpose of these tools was to integrate specific aspects of design and manufacturing.

Electronic engineers developed the design tool Magic, a VLSI Layout System, to assist in integrated-circuit design [Ousterhout 84]. The tool assists designers in locating design violations based on manufacturing criteria. The system incorporates expertise about design rules and connectivity directly into the layout system, thereby providing feedback to the designer during the design process. The integrated circuit design problem is much like a quasi three-dimensional problem with multiple layers; therefore, it does not deal with many similar issues that MEP coordination must. Due to the nature of integrated circuit design, the tool is limited in its visualization capability.

3.5 Summary of Related Research and Point of Departure

Figure 3.2 compares selected research efforts that perform configurational, based on three criteria: the intensity of knowledge, the level of configurational intensity, and the level of multi-disciplinary effort required in the tool.

As shown in Figure 3.2, commercially available CAD tools can handle many disciplines. However, they contain relatively no knowledge other than the geometric definition of objects in the model. Fischer's COKE, on the other hand, is very knowledge-intensive but does not integrate many disciplines. COKE captured and represented design-relevant constructibility knowledge to help designers check for constructibility issues during early concrete design [Fischer 97]. CADDIE and SightPlan equally require a similar level of configuration intensity and knowledge, but are limited in their ability to integrate additional disciplines.

I build from the concepts of these prior research efforts to apply knowledge from multiple disciplines to identify problems, first by identifying multiple types of interferences, and then by providing advice for resolving coordination problems. Previous research demonstrated successful use of knowledge from other disciplines in computer tools, such as Fischer's work in constructibility analysis of concrete structures. Fischer's COKE model is the closest available tool that attempts to address a problem similar to MEP coordination. It assisted designers in checking the constructibility of conceptual concrete design using criteria related to concrete formwork and assisted designers in checking the contractors' ability to use different types of concrete formwork. The COKE model provided very useful background for this research by demonstrating the feasibility of using a symbolic model for vertical integration.

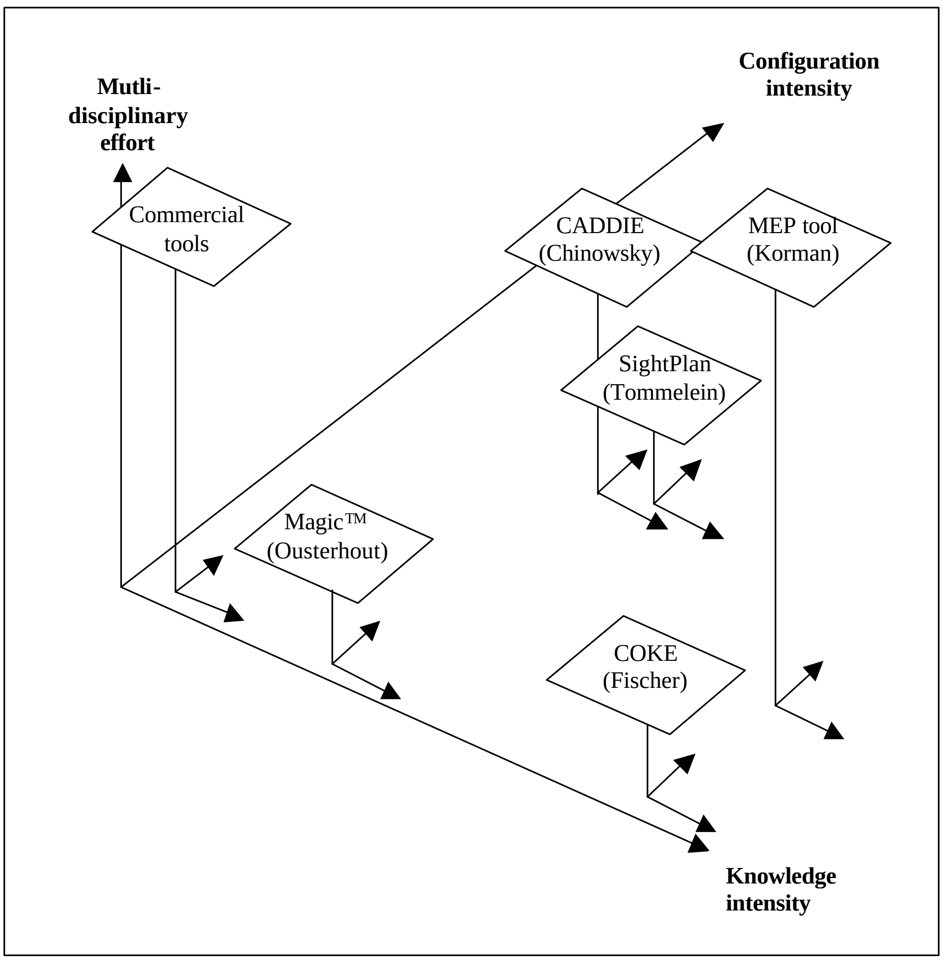


Figure 3.2 - Comparison of selected research efforts

My research lays the foundation for developing a knowledge framework and reasoning structure that is able to include many disciplines while it integrates a vast knowledge base to solve configurational tasks necessary for MEP coordination. In this research, I identified the knowledge required for multi-trade coordination from multiple experts about multiple systems and project phases including design, construction, operations, and maintenance. In addition, I formulated a knowledge framework and developed a reasoning structure to use this knowledge to resolve coordination conflicts. I integrated the requirements of the multiple-trades into the knowledge framework by selecting essential object attributes that are necessary for coordination of these systems. Furthermore, the reasoning structure determines when and why a specific system will have priority over another system in a specific area of a building or facility and provides a specific solution.

Chapter 5 will describe in detail the knowledge framework and reasoning structure developed in this research. Chapter 4 describes the specific research methodology and activities taken to develop the knowledge framework and reasoning structure, along with further expanding the point of departure.

Chapter 4 – Research Methodology and Activities

This chapter presents the methodology used in this research to build the knowledge framework, to develop the reasoning structure, and to develop the computer tool. It also describes the activities necessary to meet the objectives of this research and answer the questions posed in Chapter 1.

4.1 Building knowledge frameworks

Building and developing knowledge frameworks includes two parts: knowledge acquisition and knowledge representation. I describe both below, along with the most frequent problems associated with these activities. In addition, I describe the steps followed in this research to avoid these problems.

4.1.1 Knowledge acquisition

Knowledge acquisition begins with choosing and defining the tasks that the knowledge-based system or expert system is to perform. These tasks directly affect the type of knowledge acquired; therefore, knowledge acquisition becomes the transfer or transformation of potential problem-solving knowledge from one source to another [Dym 91]. Therefore, acquiring knowledge becomes extremely important in building knowledge frameworks. 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
- work experience in an actual coordination effort.

Review of written information sources is often a very effective initial technique for acquiring knowledge. Possible sources include trade journals, books, government publications, company procedure manuals, and current and historical project data. These materials provide information in a very unobtrusive manner. No expert time is required and knowledge engineers can accomplish most of the review independently by studying project documents [Carrico 89]. The majority of construction knowledge originates from experience in previous projects and requires a feedback loop that crosses organizational boundaries. Currently, there are no generally accepted methods to formalize construction knowledge [Luiten 98]. Therefore, researchers collect an abundant amount of written information [Carrico 89]. In this research project, data from current and completed construction projects was the primary source of written information since very little published information is available about MEP coordination.

The personal interview is one of the most effective ways to gain expertise and to receive immediate feedback. Communication with experts is essential. It allows researchers to acquire a portion of the "domain vocabulary" experts develop to deal with specific types of problems in their field. It is preferable to consult more than one expert for multiple perspectives on the problem [Carrico 1989]. In this research, I conducted interviews with engineering managers, design engineers, MEP coordinators, detailers, and construction journeymen.

Observations of experts on the job and in project meetings are also excellent ways to gather information and to understand how participants exchange information. One is able to observe experts involved in MEP coordination naturally without feeling that they are being put on the spot. This allows observation of how they deal with actual problems and how they handle surprises during problem-solving sessions. This process helps to define the problem and feeds further stages of knowledge acquisition [Carrico 89]. At the beginning of this research, I observed many experts on the job by attending the complete series of MEP coordination meetings for the McCullough Annex Building on the Stanford University campus.

After gaining knowledge about MEP coordination in the field during the initial knowledge acquisition stages, I found that work experience provided me with an excellent opportunity to deepen my understanding of the problem and process. It allowed me to take part in the process as a quasi-expert and assist in the problem-resolution effort. The knowledge gained during work experience is extremely valuable; however, it is vital that knowledge engineers write it down. Quite often, experience-based knowledge becomes second nature and experts do not document it. During this research, I gained valuable additional knowledge serving as an assistant MEP coordinator for Hathaway Dinwidde Company (HDDCO) on the Sequus biotechnology pilot plant in Menlo Park, CA.

Knowledge engineers encounter many problems in attempting to collect the necessary knowledge for a knowledge-based system. The main ones are availability of knowledge sources, quality of knowledge sources, and problems with knowledge filtering [Giarratano 98]. When knowledge acquisition begins, the first question to ask is if there are sufficient sources available to supply knowledge? This also requires experts in the field who are willing to assist in the knowledge-acquisition stage and who can devote ample time to this activity [Giarratano 98].

Following the identification of knowledge sources, their quality must be determined. This question is very important, whether the sources are written documents or experts in the field. If the sources are experts, the researcher must determine if they are capable of communicating their knowledge, judgment, and experience regarding the problem. For this research, I evaluated expert sources based on their frequency of involvement in MEP coordination-intense projects. If the source is a written document, the researcher must determine how the source will apply to the research and what value it will add. Here, I evaluated written sources according to the content that pertained to MEP coordination.

Once knowledge engineers have collected the knowledge, it is inevitable that problems arise. These are often associated with filtering the knowledge. In collecting knowledge from experts, frequently they gave no definitive answers to questions, creating problems associated with the depth of knowledge acquired [Giarratano 98].

This research used the following techniques to reduce problems of knowledge acquisition:

- triangulation to capture knowledge about the same subject from multiple sources
- an industry advisory group to collect and structure knowledge
- test cases based on historical and current projects.

Using triangulation balanced the type and quality of knowledge obtained. I collected similar knowledge from independent sources. I balanced the sources between owners, architects, design engineers, and specialty contractors. Upon completion of the knowledge collection, I compared similar knowledge from the different sources. This comparison supported conclusions regarding the validity and quality of the knowledge collected. One example of using this technique was gathering data about the components and objects that I represent in the prototype tool. I questioned architects, engineers, and contractors concerning the importance of specific components. Analysis of these data identified overlaps in the responses and helped form a conclusion.

The Industry Advisory Group for this research consisted of individuals from each type of firm involved in MEP coordination. The members ranged from vice presidents responsible for all operations to detailers who were involved in MEP coordination on a frequent basis. Appendix C lists the members and their respective organizations and includes examples of the types of input they provided.

4.1.2 Knowledge representation

Once the knowledge acquisition stage was completed, I encoded the knowledge in a form usable by a knowledge-based system (KBS). Most knowledge engineers consider this step the most critical activity. The goal is to create a structure that reflects the complexity and variety of all the components, yet remains simple enough to facilitate decision-making and assist in problem solving. Therefore, the trade-off a knowledge engineer must is between trying to represent the knowledge completely and creating a robust reasoning structure [Hunter 93]. Chapter 5 describes how I approached this trade-off.

Object hierarchies and slot tables serve as the primary form of representation in this research. The structure of the object hierarchy is important because its layout determines how the represented objects interact with each other in the symbolic model. The attributes of the slot tables also require careful study because these slots determine what data about objects are stored.

Good representation of knowledge should make things very explicit and expose natural constraints that are inherent to the problem being solved [Hunter 93]. Representing knowledge from large domains is difficult; the larger the domain, the more the difficult is becomes to create a reasoning structure [Carrico 89]. A key limitation in knowledge representation is the inability to account for all possible global interactions in the representation structure [Hunter 93]. Other problems often arise when structuring knowledge into flowcharts to provide a basis for good decision-making. These include overlap of knowledge representation overlap and incorrectly classifying knowledge.

For this research, in order to the meet the objectives and avoid these problems, I limited the number of components represented in the geometric model 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, I paid specific attention to how the reasoning structure would use the knowledge framework.

4.2 Building reasoning structures

Reasoning structures found in knowledge-based systems perform diagnostics. The reasoning methods described below provide a general framework for the reasoning commonly found in these systems.

Reasoning typically uses the following methods: heuristics, model-based reasoning (MBR), and case-based reasoning (CBR). A KBS can use heuristics, MBR, or CBR only, or it can combine two, or all three, of the reasoning methods [Kunz 95]. The intent of this research was to assist engineers in coordinating MEP systems at the design stage that requires integrating design, construction, operations, and maintenance knowledge. In this research, I used heuristics and MBR to provide the necessary feedback for MEP coordination. I describe the reasoning method and it use by the computer tool below.

4.2.1 Heuristic reasoning

Heuristics provide a basis for reasoning mechanisms in classic expert systems. A traditional KBS uses heuristics to express its knowledge. The heuristic classification system works by abstracting measurable data and relating them to a predefined potential problem. The system matches the problem with a solution, and then refines the solution. Heuristics can represent many different kinds of knowledge. They may express aspects of fundamental principles, experimental rules of thumb, and high-level knowledge about how to use other kinds of knowledge [Dym 91]. Figure 4.1 shows how a heuristic reasoning structure works.

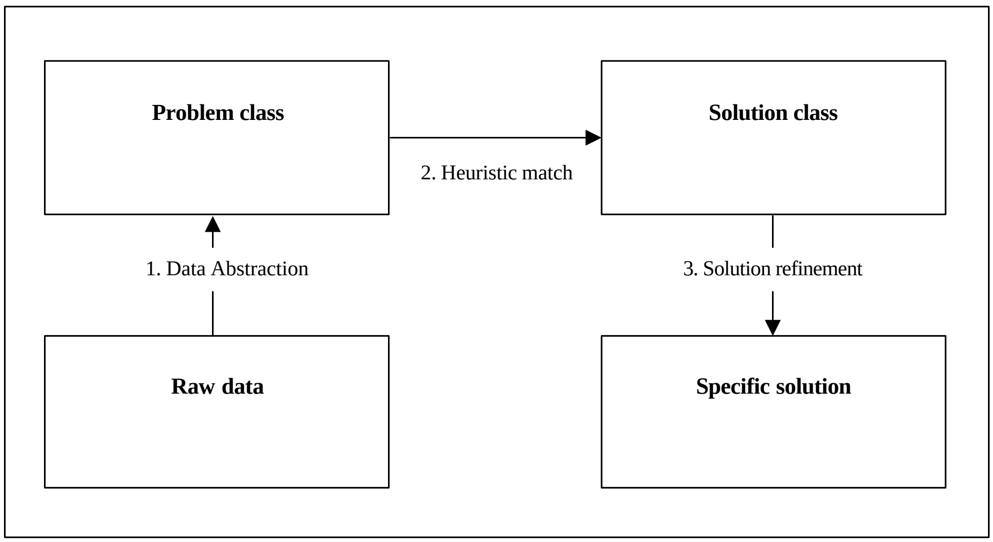


Figure 4.1 - Heuristic reasoning structure

In this research, I chose to use the heuristic reasoning because it able to match the human process for resolving coordination conflicts, as I described in Chapter 2. It lends itself well to programming the MEP coordination tool to determine and resolve coordination problems. First, the heuristic reasoning structure is able to abstract coordination information (raw data) from a CAD model. Second, the reasoning structure can then classify the conflicts by classes by making heuristic matches. Finally, the solution refinement mechanism can select a specific solution to resolve coordination conflicts. Chapter 6 gives detailed examples of how the heuristic reasoning structure performs in the prototype computer tool for MEP coordination.

4.2.2 Model-based reasoning

Model-based reasoning (MBR) involves creating a product model to form the basis for the reasoning mechanism. In this research, the geometric representation inside the computer tool serves as the model. In order to use heuristic reasoning effectively, MBR is essential. MBR provides the means to create a virtual representation of the building systems. Groups of individual components from each building system collectively comprise the product model. For reasoning purposes, each component consists of a description of the information needed to represent and reason about the component; experts often refer to this as component definition [McKinney 97].

Heuristic reasoning uses MBR to abstract, test, and analyze data. The advantage of MBR is the ability to abstract graphical, geometrical, topological, and behavioral characteristics from the components in the model for the reasoning processes. In this research, MBR reasoning tracks the effects of the geometrical and topological changes made during the resolution of coordination issues and conflicts found by the MEP coordination tool. Chapter 6 describes detailed examples of I used MBR in this research.

4.2.3 Case-based reasoning

Case-based reasoning (CBR) uses pre-formulated solution sets for a specific problem as the basis for the reasoning mechanism. In CBR, an expert creates a set of cases, each of which includes some descriptions of a situation and an associated statement of the problem's cause and suggested correction method. Reasoning essentially involves matching observed data with the data of each case. The advantage of CBR is its ability to test a prototype solution through a series of libraries that contain alternative solutions. This method can find an optimal solution. The prototype solution can also be refined to meet the specific needs of the problem at hand [Dym 91]. In this research, CBR is not used due to the number of diverse solutions possible for resolving coordination issues and conflicts. Heuristics and MBR provide a more robust reasoning system because they rely more heavily on individual component attributes rather than solution sets as used with case based reasoning.

4.3 Computer tools and knowledge-based systems

One of the products of this research is a computer tool that assists in MEP coordination.

The tool enhances the availability of knowledge during the coordination process. In developing a computer tool, we must ensure that its capabilities match the needs of the users. But what makes a good computer tool? To answer this question, one must sort out a number of issues. The most common are the following [Carrico 89]:

- there must be clear understanding of the goals of the computer tool
- the capabilities and features of the tool must be well defined
- the tool must be relativity easy to use
- an implementation plan must guide use of the tool.

4.3.1 Goals, capabilities, and features

The developer of the tool must have a clear definition of the goal of the system. In this research, the goal was to integrate a number of knowledge bases - design, construction, operations, and maintenance - into a knowledge-based system that is able to use component attributes to assist in resolving coordination problems. Very often, problems such as these are difficult to solve. The developer is tempted to expand the scope beyond reasonable limits. Consequently, the following kinds of questions arise: What is the purpose of the tool? Why is a knowledge engineer developing this tool? What capabilities and features will the tool have? We need answers to these questions to formulate a clear vision of the tool [Schutzer 1987]. Chapter 6 answers these questions.

The identification of the tool's tasks, features, and functions also directly affects the way a knowledge engineer expresses in the knowledge base and the way the tool is used [Carrico 1989]. Before I began tool development, the Industry Advisory Group (IAG), (listed in Appendix B), assisted in clearly defining the capabilities and features of the MEP coordination tool. The IAG also provided input regarding how they would use this system, suggested priorities, and provided comments regarding the capabilities of the tool.

4.3.2 Ease of use

Users consider expert systems worthless if they cannot communicate with them. They must be able to apply the tool with a relatively low level of difficulty. Therefore, the user interface is a very important aspect of the tool. The user interface should be useful, educational, and able to explain its advice [Mishkoff 1985].

Based on input from the IAG, this research gave special attention to how users would use the coordination tool, such as obtaining feedback from the tool. The IAG addressed issues regarding the date input, knowledge feedback, and user interface. Since I intended the tool developed in this research to be a prototype for use in industry, the IAG commented on the development of the tool throughout the research. Chapter 5 discusses this is detail.

4.3.3 Implementation plan

Tools often evolve with no implementation plan in mind. An implementation plan must consider issues such as portability and life cycle as well as explain how multiple members of the project team will use the tool. Input from the Industry Advisory Group guided preparation of the implementation plan for the users of this tool. Chapter 8 describes the plan.

4.4 Research Activities

The initial goal of this research was to describe current practice, because the published background lacks a complete description of the MEP coordination process. This activity was essentially completed under an initial CIFE seed project, "Improving MEP Coordination of Building and Industrial Projects." I summarize these results in Chapter 2.

Following this new understanding, I sought to demonstrate the feasibility of capturing and using this required knowledge in a computer tool that could provide advice for MEP coordination. The research objectives this evolved to include are as follows:

- developing a knowledge framework and reasoning structure for the MEP coordination process
- demonstrating the technical feasibility of representing and applying the knowledge in a tool to assist with MEP coordination
- providing recommendations for further research and practice

The following activities were required to meet these objectives:

- acquire and analyze knowledge
- develop a knowledge framework and reasoning structure

- develop and validate the computer tool.

4.4.1 Acquiring and analyzing knowledge

Acquiring knowledge first began with identifying information that is critical to MEP coordination. I prioritized knowledge acquisition based on the suggested capabilities for the tool (See Table 4.1). The knowledge acquisition included interviews with architects, engineers, general contractors, and specialty contractors. I was attempting to identify the information required for each building system and major component involved in MEP coordination for the design, construction, operations, and maintenance phases of a project. The results of these interviews formed the basis for identifying the component attributes needed for the coordination tool.

I concluded the knowledge acquisition stage after subjecting the knowledge to review by the IAG. When the IAG agreed that I had enough knowledge to perform MEP coordination, I began developing the knowledge framework. However, as I continued to meet with industry professionals, I found there was always additional knowledge to integrate as a part of developing the knowledge framework (See Section 4.4.2).

The analysis continued by 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 or alter priority 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 step set the foundation for forming the methods used in the reasoning structure that I will describe in Section 5.2.

In addition, the analysis required determining the level and type of CAD information and representation relevant to an object or component that is needed by engineers for detailed coordination. I will describe the results of this analysis in Section 6.2.

4.4.2 Developing a knowledge framework and reasoning structure

The next step was to put the MEP knowledge into a knowledge framework and reasoning structure that was useful for solving coordination problems. I developed the knowledge framework and reasoning structure by incorporating the desired capabilities and specifications of the IAG. This development of the knowledge framework included structuring an object hierarchy, or a list of components, and fundamental blocks of knowledge. I included design-intent knowledge, construction knowledge, operations, and maintenance knowledge in the knowledge blocks.

I designed the knowledge framework and reasoning structure to be both detailed and robust. I tried to keep the classification of component attributes compact. I sorted the component attributes by project phase: design, construction, operations, and maintenance and defined a clear object hierarchy for components commonly used in building systems. The reasoning structure utilizes the knowledge framework by applying tailored solution classes and generalized heuristics to provide advice regarding coordination problems. I will describe the knowledge framework and reasoning structure in detail in Chapter 6.

4.4.3 Developing and validating the prototype computer tool

Tool development involved the following main activities:

- preparing tool specifications
- developing system architecture for tool
- implementing, testing, validating, and refining the tool.

The Industry Advisory Group for the project made specific recommendations concerning the use of the tool. They suggested the capabilities such as those listed in Table 4.1. These suggested capabilities helped me form specifications for the software application developed in this research. I used the high, medium, and low priority to determine a schedule for developing the tool. The list includes recommendations for systems to include in the geometric model and the types of analysis necessary to perform MEP coordination.

Table 4.1 – Suggested capabilities for MEP coordination tool

High priority	Medium priority	Low priority
• include all major systems in the full model required for effective coordination • capture Civil, Structural, and Architectural (CSA) for interference and support; show required penetrations, flag requirements for architectural and structural clearances • serve as space management tool; reserve space for each discipline/trade, operation and maintenance • provide real-time feedback regarding full implications of coordination decisions • provide information regarding installation sequence • highlight sequence and other constraints created by coordination decisions	• take different types of CAD inputs; help those not using CAD • support visualization of design configuration, system aesthetics, construction sequence • cut sections at any location and in any direction in the building or plant • handle special configurations, such as bus duct, valves, control boxes in duct • allow special attention to congested areas, such as around the building core • consider and support shared knowledge between disciplines and trades	• produce required as-built drawings • incorporate vendor information for all equipment and components of systems • capture craft experience for design and routing and other restraints on installation • capture knowledge for allowable solutions to frequent coordination problems • transfer data over the internet • estimate the space needed for MEP systems during very early design phases • calculate the cost of changes in design or coordination • calculate the schedule impact of changes in design or coordination • display status of design and construction for the systems • support rapid engineering response to problems • replace the slow RFI process

Since the primary purpose of the system is to assist in MEP coordination during the design stage, the system requires an architecture that can integrate the necessary knowledge required for MEP coordination. To achieve this, I designed the tool based on Figure 4.2.

The figure displays how the prototype tool integrates individual models of building systems into one composite model. The, application of the knowledge framework and reasoning structure create an intelligent model, provide feedback to users regarding coordination decisions, and assist in creating a coordinated model of the building systems. Chapter 6 further describes this tool and its capabilities.

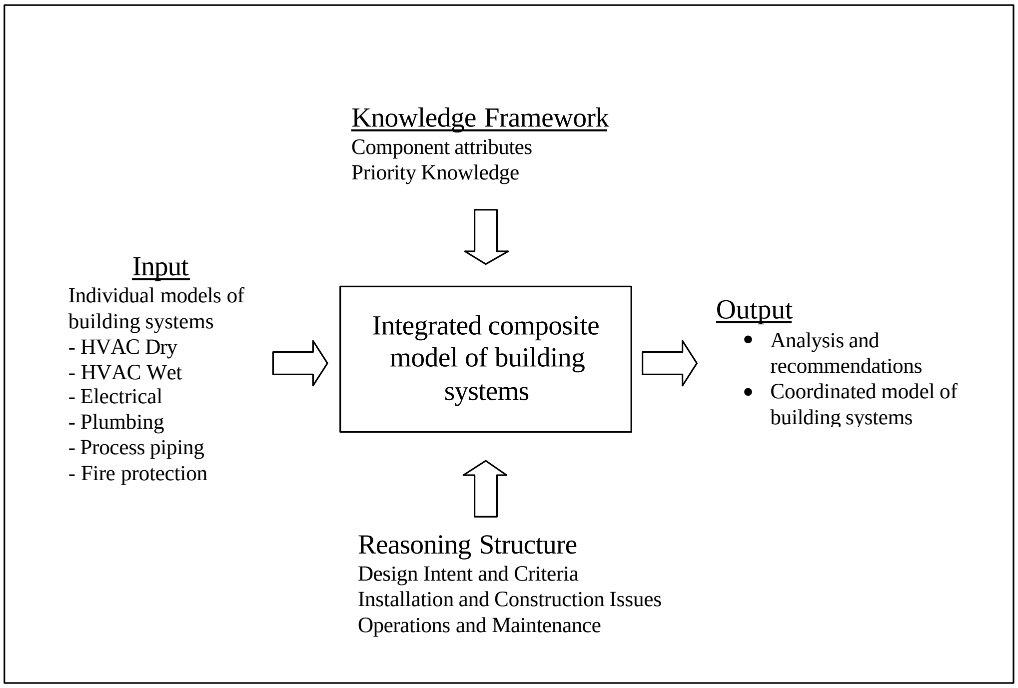


Figure 4.2 – Prototype tool conceptual model

Chapter 6 describes how I developed, implemented, tested, and validated the prototype tool. The IAG provided further feedback as a part of this process. Chapter 7 describes the retrospective and prospective test cases I used to compare the results of MEP coordination by using the tool on an actual project.

The retrospective test answered the following questions:

- In what ways did the tool produce results similar to those of the current coordination process?
- How were recommendations made by the tool contrary to the results of the current coordination process?
- Did the tool make suggestions that were an improvement over the current process results?

A prospective test case answered similar questions:

- How does the tool use the represented knowledge to assist in decisions?
- What are the similarities and differences between the advice that the tool provides and that used in the current process?

The comparative measures used to determine the similarities and differences were the measures of good coordination, as described in Chapter 2. Chapter 7 will present the results of these test cases to demonstrate the use of the knowledge framework and reasoning structure. Based on the results of the test cases and the reaction of the Industry Advisory Group, I refined the user interface and the knowledge representation scheme.

The methods and activities described in this chapter allowed me to achieve the research objectives of developing a knowledge framework and reasoning structure for use in the prototype tool. Before describing the prototype tool, the next chapter will focus on the content of the knowledge framework and logic of the reasoning structure. These are the critical components of the prototype tool and they made it possible to demonstrate technical feasibility.

Chapter 5 – Knowledge framework and reasoning structure

Although the most visible parts of MEP coordination focus on the geometry and functionality of the building systems, as discussed in Chapter 2. Improving the coordination process for MEP systems requires a wealth of knowledge regarding MEP systems and the buildings they serve. Therefore, MEP coordination provides a major opportunity to structure and integrate the knowledge into a format that allows users to improve project performance. This research integrates design, construction, and operation and maintenance knowledge of the building systems. The knowledge framework and reasoning structure is the result of this integration effort.

The knowledge framework contains specific object attributes and characteristics about MEP systems. The reasoning structure applies knowledge to identify multiple types of interferences and to assist in resolving coordination problems related to design requirements, construction requirements, operations, and maintenance of the facility. It also allows the computer tool to identify detailed criteria that the coordinated MEP design must satisfy and give advice regarding solutions that satisfy multiple constraints.

The first section of this chapter describes the knowledge framework in detail and includes tables and figures to describe component attributes and characteristics. The second section describes the reasoning structure and the mechanisms used in it. The third section provides an example outlining how the knowledge framework and reasoning structure work together to resolve a specific interference.

5.1 Knowledge Framework and Representation of Coordination Knowledge

The computer tool 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, operations, and maintenance. The knowledge collected for each domain assists in MEP coordination.

I describe the most pertinent aspects of each domain below. Figure 5.1 provides an overview of the type of knowledge collected in the knowledge framework.

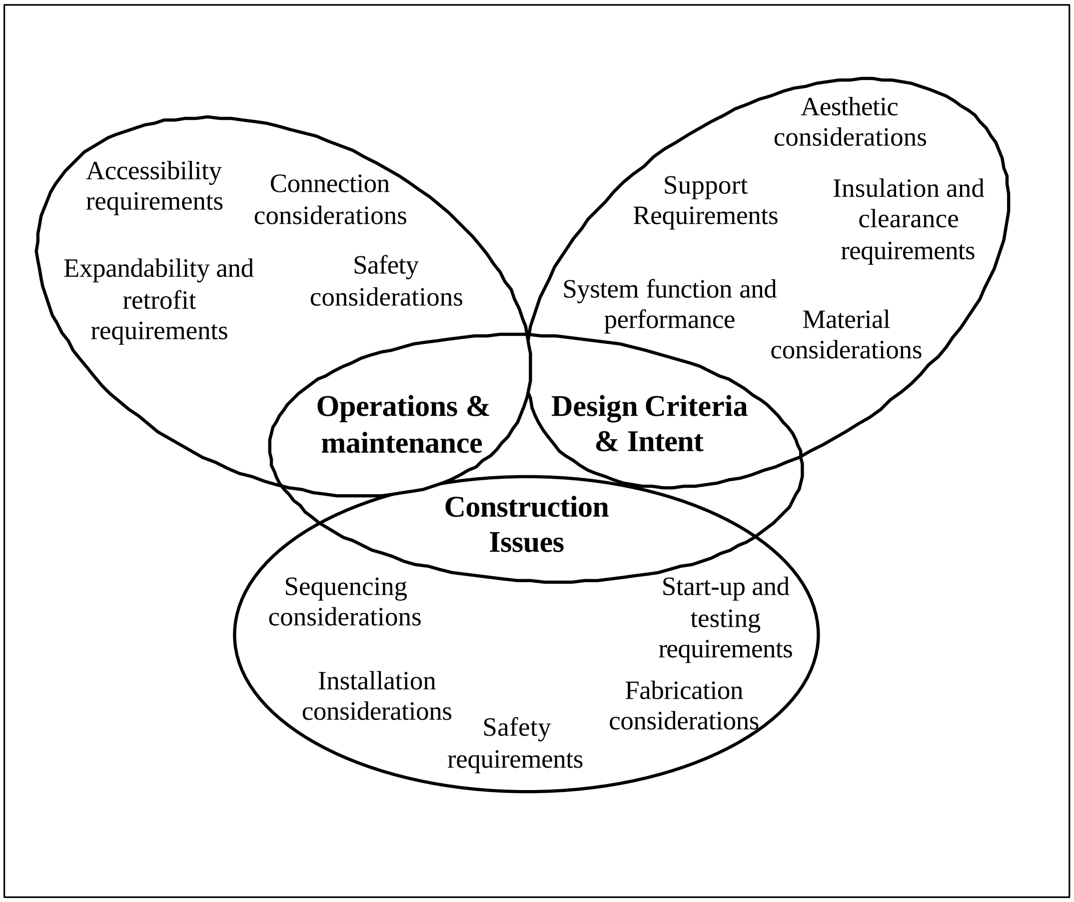


Figure 5.1 - Integration of knowledge bases required for MEP coordination

5.1.1 Design knowledge

Design engineers and detailers bring design knowledge regarding each type of system to the MEP coordination process. They apply this knowledge during MEP coordination to assure that the systems satisfy performance requirements for the specific project and comply with codes and standards. Table 5.1 lists the attributes of a component related to the design criteria and intent. Figure 5.2 illustrates those attributes that require space reservation.

Table 5.1 - Knowledge related to design criteria and intent

Attribute Name	Explanation
Function	Designates the primary performance function of the component Examples: A light fixture illuminates. A sprinkler head sprays water.
System	Designates the system to which the component belongs Examples: A slot diffuser belongs to the HVAC dry system; a heating water return pipe belongs to the HVAC wet system.
Material type	Designates the material or choices of material used for a specific component Example: Choices for supply air duct material includes aluminum, galvanized steel, sheet metal, stainless steel, or fiberglass.
Material cost	Designates the cost of the component (per vendor data or estimating standards) Examples: Sprinkler line fabricated from 2"diameter black steel pipe costs $1.57 per linear foot.
Support system	Designates the typical system used to support the component Example: Electrical conduit may rest on pipe racks that contractors attach to walls or hang from trapeze hangers.
Insulation	Designates the insulation type and thickness of a particular component; possible types include: fire protection, thermal energy conservation, sound isolation, anti-sweat, and personnel protection Example: The insulation thickness required for heating water supply lines is 1-1/2".
Clearance	Designates the design clearance requirements of components to prevent heat exchange, to mitigate vibration concerns, or to minimize signal crossing in communications lines Example: The required clearance between heating water supply and heating water return lines is 6".
Slope	Designates the required slope for a component. Example: gravity-driven wastewater drain lines should slope 1/8" per foot.

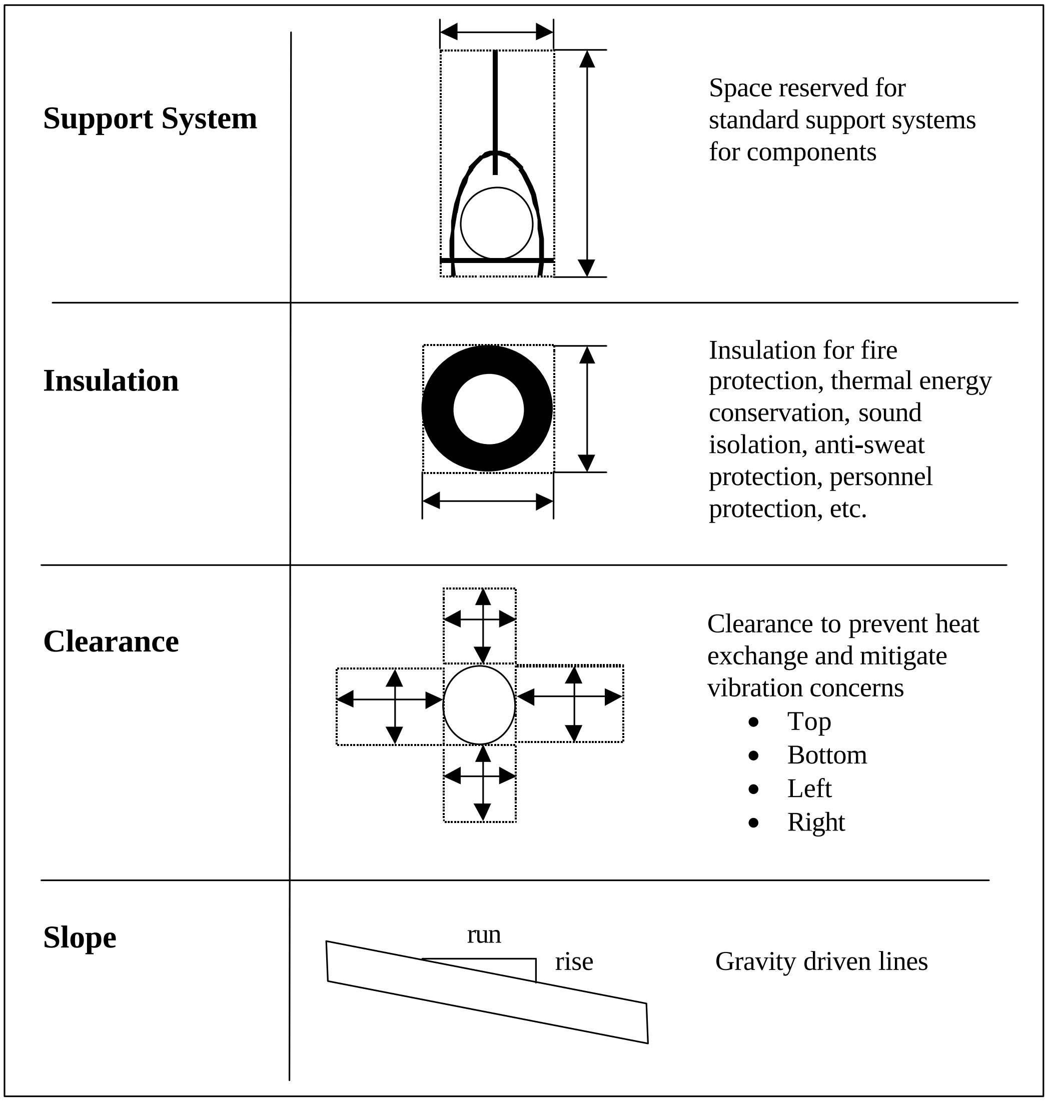


Figure 5.2 - Pictorial description of design criteria and intent attributes

5.1.2 Construction knowledge

The tool developed in this research applies construction knowledge during MEP coordination to assure feasible designs for building the systems and to increase the efficiency of field operations. The construction knowledge includes installation access requirements, construction sequences and methods, and lead-time for components. Superintendents, foremen, and engineers familiar with field operations provide this knowledge. Table 5.2 lists the attributes of a component that relate to the construction phase. Figure 5.3 illustrates attributes that require space reservation for construction operations.

Table 5.2 - Construction knowledge

Attribute Name	Explanation
Installation space	Defines and reserves space for installation of components. This includes space around the component for construction craft persons, materials handling and storage, and construction equipment Example: Construction craft pulling electrical cable requires five feet of access space from the end of the conduit.
Installation sequence	Designates typical installation of components considering start-up, testing, commissioning, and turnover requirements in order to maximize prefabrication Example: Installation of air terminal boxes always precedes air-distribution ducts.
Lead time	Designates the average lead-time for fabrication of a component Example: VAV boxes typically require a lead-time of 2 weeks.

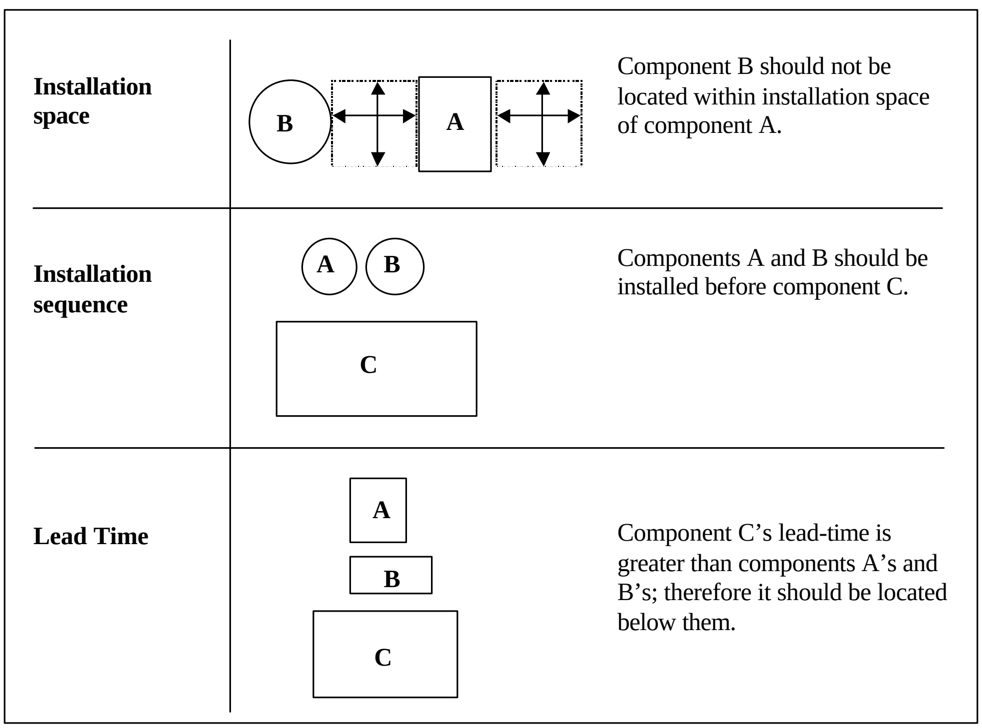


Figure 5.3 - Pictorial description of construction class attributes

5.1.3 Operations and maintenance knowledge

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 lifecycle 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. Table 5.3 lists attributes of a component that relate to operations and maintenance. Figure 5.4 illustrates attributes that require space reservation.

Table 5.3 - Operations and maintenance knowledge

Attribute Name	Explanation
Access Space	Defines and reserves space required for operations and maintenance Example: Access space required by personnel for valves is typically 12” depending on the type of valve.
Access frequency	Designates the access frequency required to maintain a component Example: Expected access to sprinkler heads is once per month.

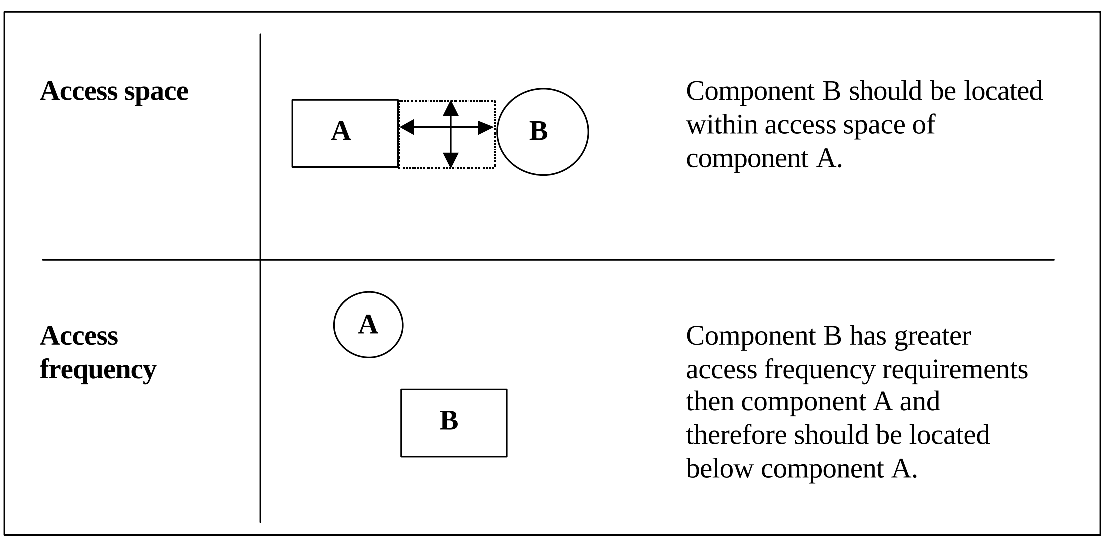


Figure 5.4 - Pictorial description of operations and maintenance class attributes

5.2 Reasoning Structure for MEP coordination

In Chapter 4, I described two essential parts of the reasoning structure used in this research – model-based reasoning and heuristic reasoning. I describe each of their uses in this research below.

5.2.1 Model-based reasoning

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

Geometrical 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. MBR allows the tool to maintain updated knowledge concerning the size and dimensions of components as well as the location of each component and its relative position with other components, known as spatial adjacencies.

In this research, I represent objects in the product model using their upper and lower bounds. Figure 5.5 displays the coordinate information recorded. When individual components are commonly associated with an assembly, such as valve stations, consisting of multiple valves and pipe loops, I represent the entire valve assembly, with one bounding box. The prototype tool automatically uses the upper and lower bounds to identify interferences in the model as well as the spatial relationships and spatial adjacencies between objects. Tables 5.4 and 5.5 identify geometric and topological characteristics that the prototype tool abstracts from the geometric model for each component.

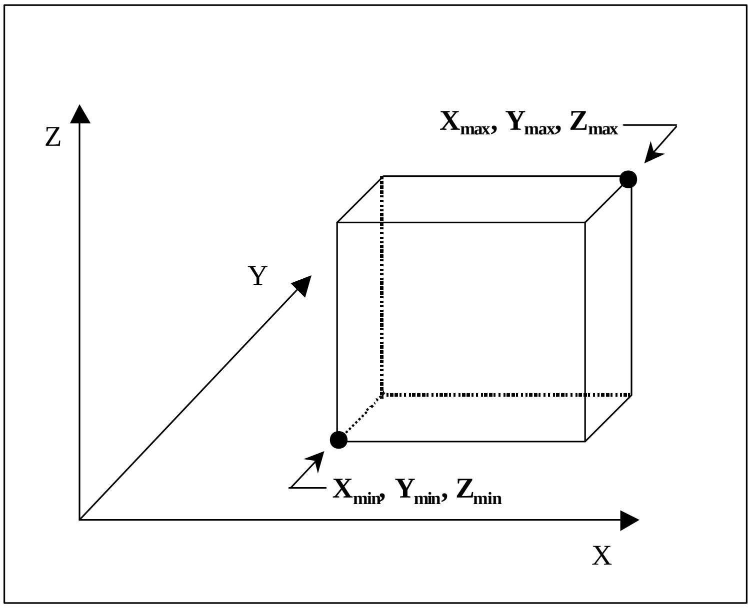


Figure 5.5 – Upper and lower bounds of component bounding box

Table 5.4 - Geometric characteristics

	Geometric Characteristic Name					
Coordinate Information	X_{max}	Y_{max}	Z_{max} (Top elevation)	X_{min}	Y_{min}	Z_{min} (Bottom elevation)
Component Dimensions	Height (diameter)	Width (diameter)	Length	Cross sectional area		
Connections	Number of vertical connections per length	Number of horizontal connections per length	Overall line length			

Table 5.5 - Topological characteristics

	Topological Characteristic Name		
Location	Is located in room	Is located in facility	
Spatial Relationships	Is part of system	Is connected to	
Spatial Adjacencies	Is located next to (left or right)	Is located above	Is located below

5.2.2 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 coordination issues for a specific type of interference, as identified in the next section. Figure 5.6 displays how the tool developed in this research uses heuristic reasoning.

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 (see Table 5.6). By using heuristic matching, the reasoning structure identifies one of the following solution classes: detailing, layout, positioning, application, or scheduling. Once they determine the solution class, designers can select a specific solution set using heuristics. Symbolic modeling literature refers to this as solution refinement. I describe each of these steps – data abstraction, heuristic matching, and solution refinement – in more detail below.

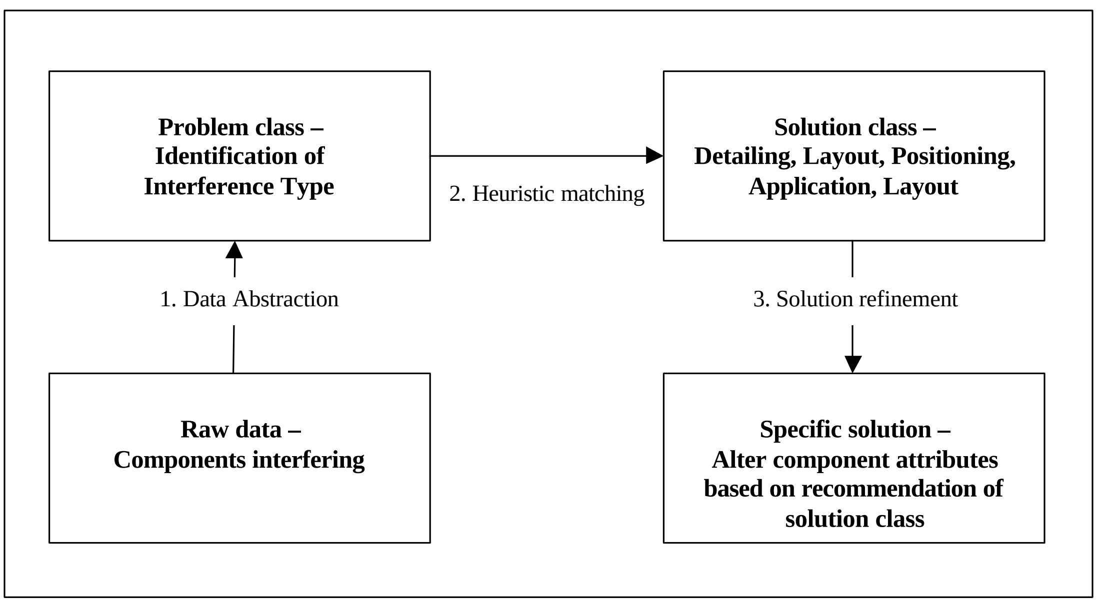


Figure 5.6 - Heuristic reasoning structure for tool

5.2.3 Data abstraction - Identification of types of interferences

As a part of analyzing the knowledge obtained from observing experts during coordination meetings and other sources, I was able to identify and classify the five most common types of interferences found in MEP coordination. Table 5.6 defines these intereferences.

Table 5.6 - Type and description of interferences identified in the tool

Interference Type	Description
Actual	An actual (physical) interference occurs when two or more components physically interfere.
Extended	An extended interference occurs when a component interferes with an extended space that is associated with another component.
Functional	A functional interference occurs engineers position two or more components such that their location in relation to each other jeopardizes the intended function of the component.
Temporal	Time-related interferences occur when engineers position components in a manner that prevents efficient construction sequencing and scheduling.
Future	A future interference occurs when engineers position components in locations that they do not allow space for routine operations and maintenance tasks or space for future expansion.

The MEP coordination tool is able to identify instances of each type of interference listed in Table 5.6. Most current commercial computer tools can identify only actual interferences, and only a few are able to identify extended interferences (see Chapter 3). However, to meet the indicators of good coordination (Section 2.5.3), one must also consider functional, temporal, and future interferences during MEP coordination. Figure 5.7 represents the interferences identified by the prototype tool for MEP coordination.

The reasoning structure identifies interferences by evaluating the attributes of each component in the geometric model. Table 5.7 designates the component attributes and characteristics used to classify interferences. 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.

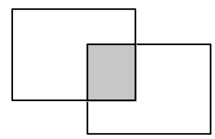
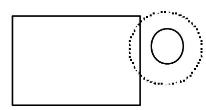
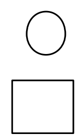
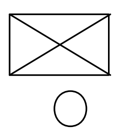
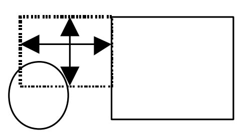
Actual		Two or more components physically interfere with each other.
Extended		Components interfere with extended zones associated with other components.
Functional	 Example: Waste line located above electrical bus duct may affect function of bus duct if leaking occurs.	Components are positioned such that their location jeopardizes the intended function of another component.
Temporal	Example: Construction sequence indicates fire protection line to be installed prior to HVAC duct. 	The positioning of components affects the typical installation sequence.
Future		The layout of components affects future ability to perform operations and maintenance tasks.

Figure 5.7 - Pictorial description of types of interferences identified in computer tool

Table 5.7 - Component attributes and characteristics used to classify interferences

Interference type	Geometric and topological characteristics	Design criteria and intent attributes	Construction attributes	Operations and maintenance attributes
Actual	• Coordinate information • Component dimensions	• Insulation • Support system		
Extended	• Coordinate information • Component dimensions	• Clearance • Material cost		
Functional	• Coordinate information • Component dimensions • Location • Spatial relationships • Spatial adjacencies	• Material type • Slope		
Temporal	• Coordinate information • Component dimensions • Location • Spatial relationships • Spatial adjacencies • Connections		• Installation sequence • Lead time • Installation space	
Future	• Coordinate information • Location • Component dimensions • Spatial relationships • Spatial adjacencies • Connections			• Access space • Access frequency

5.2.4 Heuristic matching – Selection of solution classes

After classifying the types of interferences found in the geometric model, the tool uses heuristic matching to determine a general solution for resolving the interference. This research identified six solution classes used to resolve coordination problems. They are detailing, layout, positioning, application, and scheduling. Table 5.8 defines these solution classes.

Table 5.8 - Solution classes used in reasoning structure

Solution classes	Definition
Detailing	Modify detailed design of components, such as size, insulation, and support system
Layout (horizontal)	Move components along their horizontal plane
Positioning (vertical)	Move components along their vertical plane
Application	Alter design intent and performance of components
Scheduling	Adjust installation sequence and scheduling related attributes

Fischer's COKE model used solution classes that focused on the constructibility issues regarding specific structural elements – beams, slabs, columns, and walls. For these particular structural elements, COKE considers the three solution classes – detailing, layout, and positioning [Fischer 97]. The reasoning structure I developed uses the component attributes to determine interferences and select possible solution classes (see Table 5.9). For instance, if the prototype tool identifies an actual interference due to the components' insulation, the reasoning structure selects the solution classes and uses the proper heuristics to resolve a particular interference. Symbolic modeling literature refers to this as a heuristic match. The heuristic match links the component attributes and solution classes and forms the basis for the reasoning structure to provide advice regarding coordination problems.

Table 5.9 - Component attributes used the determine possible solution classes

Component attributes	Solution classes				
	Detailing	Layout (horizontal)	Positioning (vertical)	Application	Scheduling
Insulation	✓	✓	✓		
Support system	✓	✓	✓		
Clearance		✓	✓	✓	
Material cost	✓				✓
Material type	✓			✓	
Slope		✓	✓	✓	
Installation space		✓	✓		✓
Installation sequence		✓	✓		✓
Lead time					✓
Access space		✓	✓		
Access frequency		✓	✓		

5.2.5 Solution refinement – Selection of a specific solution

After identifying the possible solution classes that are available for interference resolution, the reasoning structure determines a specific solution. Symbolic modeling literature refers to this as solution refinement. Heuristics associated with each solution class provide a mechanism for resolving interferences. Tables 5.10 through 5.14 define and group the types of heuristics by solution class.

Table 5.10 - Heuristics associated with the detailing solution class

Heuristic Name	Explanation
Supportability	• Components with the larger support systems should have priority • Components with the greater number of vertical supports should have priority • Components which require seismic bracing should have priority

Table 5.11 - Heuristics associated with the layout (horizontal) solution class

Heuristic Name	Explanation
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 the number of connections needed for branch lines
Relative size	• Locate components with greater cross-sectional areas (**width** x **height**) **next to** column lines

Table 5.12 - Heuristics associated with the positioning (vertical) solution class

Heuristic Name	Explanation
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 a vertical plane to reduce horizontal space
Perpendicular path	• When perpendicular components interfere, the component with greater **overall line length** should yield to other components

Table 5.13 - Heuristics associated with the application solution class

Heuristic Name	Explanation
Functionality	• Pressurized components shall yield to other components • Gravity-driven components shall have priority • Components critical to the process in the room shall have priority

Table 5.14 - Heuristics associated with the scheduling solution class

Heuristic Name	Explanation
Installability	• Locate components later in the **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** x **height**) and greater **length, above** other components and directly below the primary structure for ease of installation
Relative length	• Locate components with greater **length** or **overall line length, above** other components or ease of installation
Similarity	• Locate components with similar **lead times** adjacent to other components with same **lead time**

5.3 Heuristic reasoning example

Figure 5.8 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 interference by evaluating the attributes in question. In this case, the two components physical interfere; however, the slope attribute of the gravity line is also in question. Therefore, the reasoning structure classifies the interference as a functional interference.

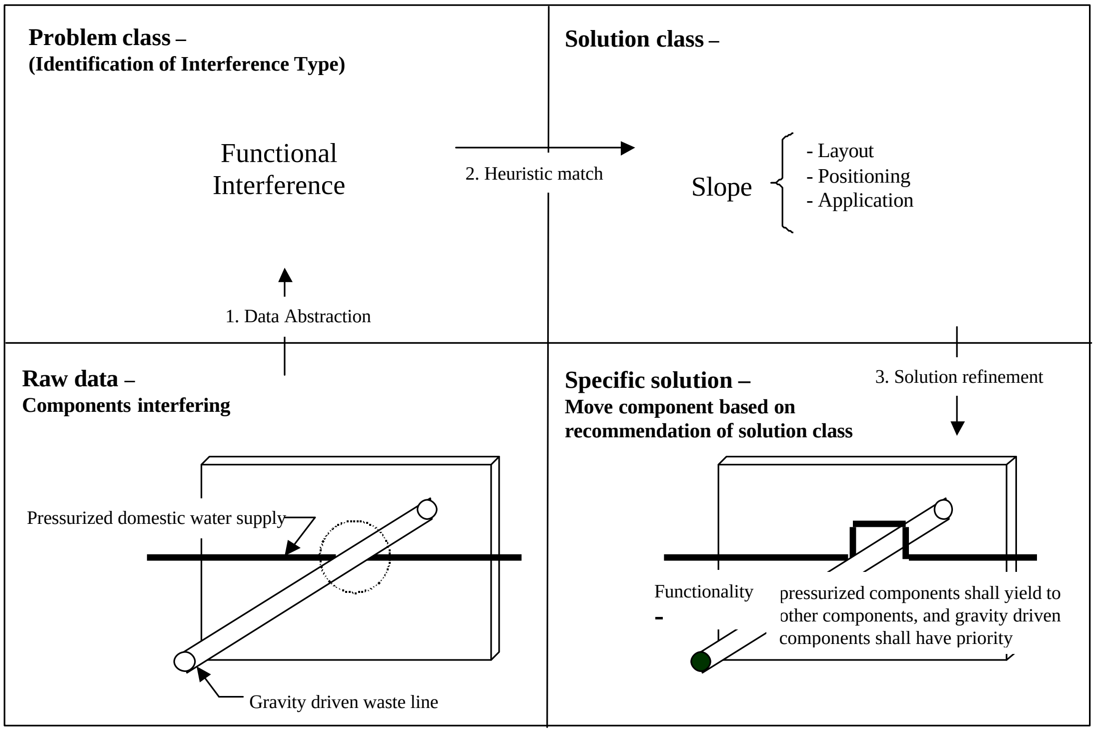


Figure 5.8 - Heuristic reasoning example

Using heuristic matching, the reasoning structure selects a solution class set from Table 5.9. The table indicates that the solution class set should include: layout, positioning, and application. This indicates that the solution will involve moving one of the components along the horizontal plane, the vertical plane, or considering the design intent attributes of the components. Using Tables 5.11, 5.12, and 5.13 the solution refinement 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 project phase: design, construction, operations, and maintenance. Furthermore, it defines a clear object hierarchy for components commonly used in building systems. The reasoning structure uses the knowledge framework by applying tailored solution classes and generalized heuristics to provide advice regarding coordination problems. Chapter 6 will further prove the value and demonstrate the significance of these two important contributions. Chapter 7 describes two test cases used to validate the knowledge framework and reasoning structure as well as describe their limitations.

Chapter 6 - MEP Coordination Tool

This chapter describes the programming structure for the MEP coordination tool. This includes a description of the system architecture, the object representation structure, and the user interface.

6.1 System architecture

The system architecture follows the structure shown in the IDEF diagram, Figure 6.1. It defines the coordination tool's input, mechanisms, control, and output.

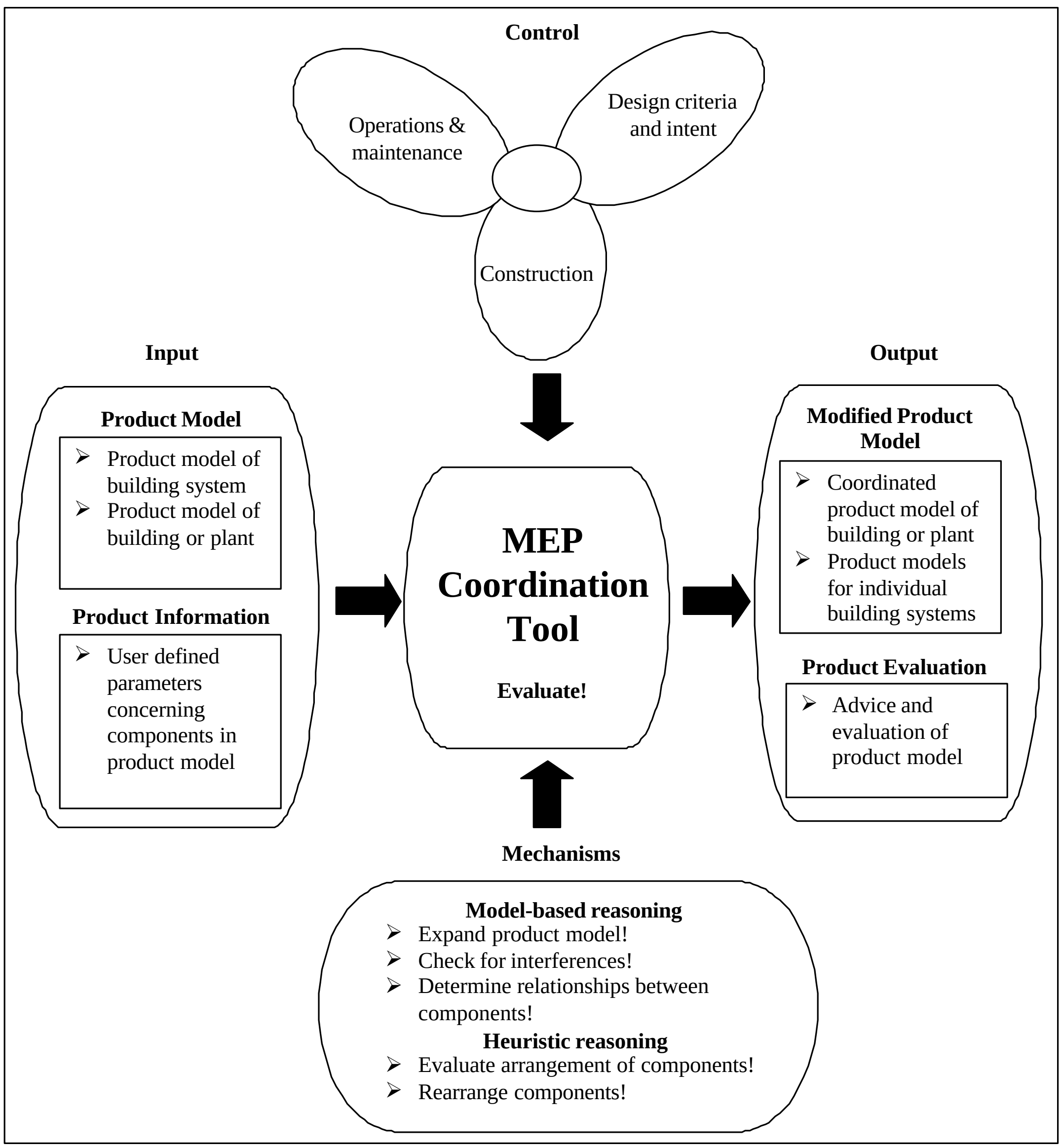


Figure 6.1 - IDEF Model for system

6.1.1 Input

The input for the coordination tools consist of a product model, which is a geometric model of the facility, and product information, which is user-defined parameters regarding components in the model.

The specialty contractors produce separate 3D CAD models for their own trade. The electronic models are loaded into the prototype tool individually. The geometric model integrates the separate 3D CAD models for each of the building systems. Together these models include all the major systems found in the facility - HVAC dry, HVAC wet, plumbing, process piping, fire protection, electrical, and controls. Section 6.2 describes the component geometric representation scheme. The product model also includes the major structural elements and architectural components found in the facility. These structural elements and architectural components of the geometric model form the facility envelope.

The user-defined parameters include specific component attributes that are project-specific. These include component cost, material type, insulation type and size, access space and frequency, installation time, and installation sequence. The database of the coordination tool contains pre-selected values for many of these component attributes; however, the user has the option to review and revise any of these.

6.1.2 Control

The integration of knowledge bases, described in Chapter 5, serves as the control for the coordination tool. This knowledge considers design, construction, operations, and maintenance requirements for each component. The component attributes include system function and performance, insulation and clearance, fabrication, installation, start-up, testing, accessibility, and safety. Section 5.1 gives a detailed description of this knowledge. The component database stores this knowledge as component attributes. The tool abstracts the data from the geometric model, and this knowledge functions as a comparison base in determining the type of interferences and for providing feedback interference resolutions as described in Section 5.2.

6.1.3 Mechanisms

The flowchart in Figure 6.2 delineates the methods used in the coordination tool. This is the implementation of the prototype tool. These mechanisms, also referred to as methods, perform the necessary data abstraction and data comparison to identify interferences in the geometric model and guide rearrangement of the components to eliminate interferences. Tables 6.1 through 6.4 describe the purpose of each method and identify the sub-methods that each method contains.

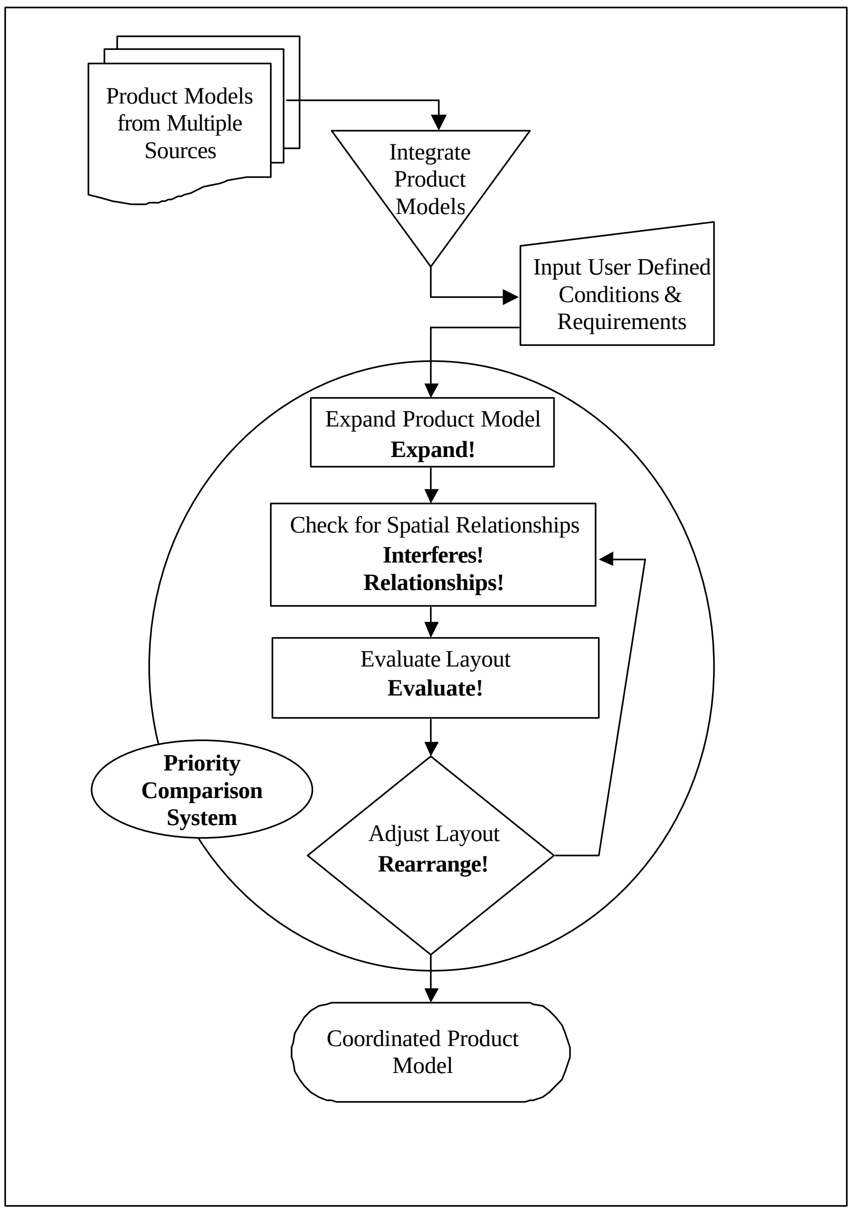


Figure 6.2 - Flowchart for MEP Coordination Tool

The Expand! method fills the component attributes that reserve additional space associated with components geometrically represented in the 3D CAD, also known as the product model. This includes information such as design clearances, insulation, pipe and duct supports, installation clearances, and access and operation space requirements. This knowledge is stored in the knowledge framework. For programming purposes, I subdivided the Expand! method into several sub-methods. Table 6.1 lists these sub-methods and provides a short description for each.

The Interferes! method implements the data-abstraction step of the heuristic reasoning structure. It has five sub-methods that determine and classify the interferences of components in the product model. Table 6.2 lists and describes these sub-methods.

The Relationships! method implements the model-based-reasoning structure which determines the topological characteristics of components in the product model, specifically the spatial relationships and spatial adjacencies. These include the component characteristics such as, **Is Located Above**, **Is Located Next to**, and **Is Located Under**. Using the coordinate information described in Section 5.2.1, the prototype tool determines other geometric characteristics of components in the product model, such as, **Number of vertical connections**, **Number of horizontal connections**, and **Overall line length**. For programming purposes, the Relationships! method contains several sub-methods. For each new product model, each sub-method calculates these component characteristics. Table 6.3 lists and describes the sub-methods of the Relationships! method.

The Evaluate! method is the implementation of the heuristic matching and solution refinement steps of the heuristic reasoning structure. The method uses the information obtained by Interferes! and Relationships! to provide advice regarding coordination.

The Rearrange! method allows the user to rearrange components based on the evaluation of the product model provided by the MEP Coordination Tool. The tool suggests conflict resolutions based on the heuristics.

Table 6.1 - Sub-methods of the Expand! method

Sub-method Name	Description
Support_Space!	Reserves space for support systems required for individual components
Insulation_Space!	Adds insulation space to components as required by design intent
Design_ClearanceSpace!	Adds clearance space to components as specified by design criteria
Install_Space!	Reserves space required for installation of component
O&M_Space!	Reserves space required for operations and maintenance

Table 6.2 - Sub-methods of the Interferes! method

Method Name	Description
Actual_Interference!	Identifies ***actual (physical) interferences*** of component in the product model
Extended_Interference!	Identifies the ***extended interferences*** of components in the product model
Functional_Interference!	Identifies ***functional interferences*** of components in the product model
Temporal_Interference!	Identifies ***temporal (time related) interferences*** of components in the product model
Future_Interference!	Identifies ***future interferences*** of components in the product model

Table 6.3 - Sub-methods of the Relationships! method

Sub-method Name	Description
IsLocated_NextTo!	Identifies components located next to (parallel) to a particular component
IsLocated_Above!	Identifies components located above a particular component
IsLocated_Below!	Identifies components located below a particular component
IsConnectedTo!	Identifies components connected to other components in the product model
Vertical_Connections!	Identifies the number of vertical connections to the component
Horizontal_Connections!	Identifies the number of horizontal connections to the component
PartOfLine!	Identifies the line to which a particular component belongs
RunLineLength!	Identifies the overall run length of a line in which the component is located
InRoom!	Identifies the room in which a particular component is located
InFacility!	Identifies the facility in which a particular component is located

Table 6.4 - Sub-methods of the Evaluate! method

Method Name	Description
Evaluate!	Provides feedback to users for resolving interferences and coordination problems

Table 6.5 - Sub-methods of the Rearrange! method

Method Name	Description
Segment!	Alters geometric properties of components based on rearrangement needed in system

6.1.4 Output

The output of the coordination tool is a coordinated product model of the entire facility. This output is valuable because it also includes the knowledge provided during feedback for interference resolution. Based on the information obtained from the multiple sources described in Chapters 3 and 4, the major criteria and constraints for MEP coordination fall into three categories: design, construction, and operations, and maintenance. Therefore, the output provides feedback about compliance with criteria from these project phases. The following table summarizes the capabilities of and outputs from the MEP coordination tool in each phase.

Table 6.6 - Capabilities and output of MEP coordination tool by project phase

Project phase	Capabilities and output
Design	• Displays location and configuration of all MEP systems, components and their respective support systems • Indicates types of interferences found between multiple systems
Construction	• Provides direct access to construction knowledge; including space necessary for installation • Highlights construction and installation sequences determined by configuration
Operations and maintenance	• Provides direct access to space requirements for operations and maintenance • Highlights necessary access requirements; including frequency and space requirements for operations and maintenance

6.2 Component classification and representation

The coordination tool classifies components in a format most easily understood by the multiple design disciplines and construction trades involved in MEP coordination. Therefore, it classifies components by building system, as the various specialty contractors would install them. In addition, the geometric model includes major structural elements and architectural elements.

The prototype MEP coordination tool developed in this research classifies the components in each system as either equipment or lines. This classification recognizes the significant differences in each type of component. For example, although an equipment item and a line are both components of an overall system, they have very different functions. The primary function of equipment is to operate with the system, typically to force flow or facilitate heat exchange. A line serves as a delivery mechanism, and thus its primary function is to carry a fluid to various points in the system. Figure 6.3 displays a pop-up window used by the prototype tool. (Note the classification scheme of lines and equipment sorted by building system.)

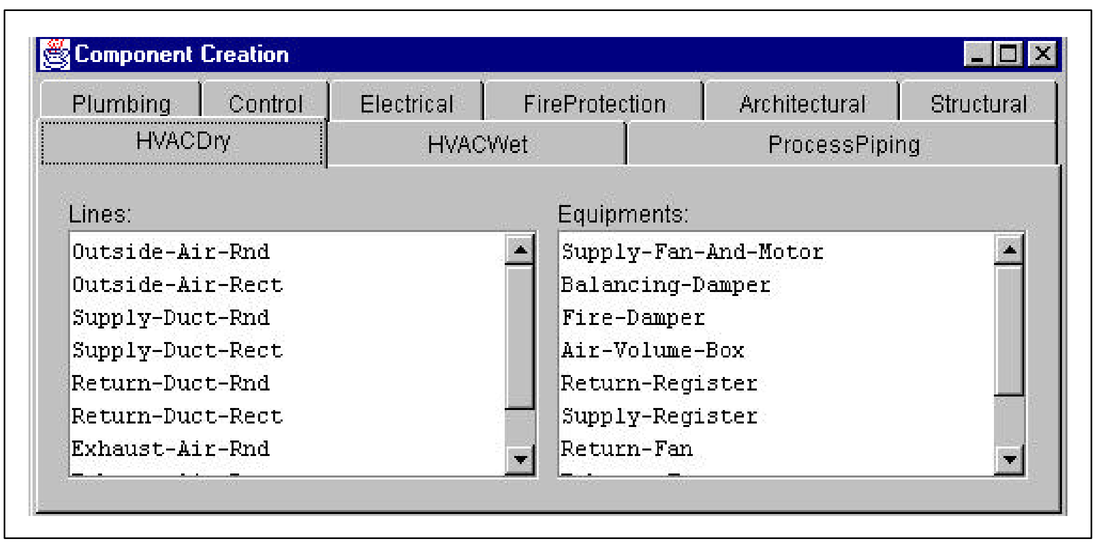


Figure 6.3 - Sample of components represented in the geometric model

6.3 User Interface

I managed the development and programming of the prototype coordination tool in the JAVA™ language to run on a personal computer. JAVA™ allows for multi-platform use. The prototype tool abstracts the geometric characteristics regarding the location and size of components from AutoCAD in the form of an ASCII text file (as described in Section 5.2.1). To display the coordinated product model of the facility, the system writes an output file in VRML in order to provide walk-through and three-dimensional rendering capabilities.

The user interface in Figure 6.4 shows the major features of the coordination tool. On the left of this screen, the user views a component tree including all of the components in the geometric model classified by their system. On the top right, the tool displays the current arrangement of components in the model. At the bottom, the tool indicates the interferences it detects, and it highlights the knowledge necessary to resolve the interferences. It classifies the interferences as actual, extended, functional, temporal, or future.

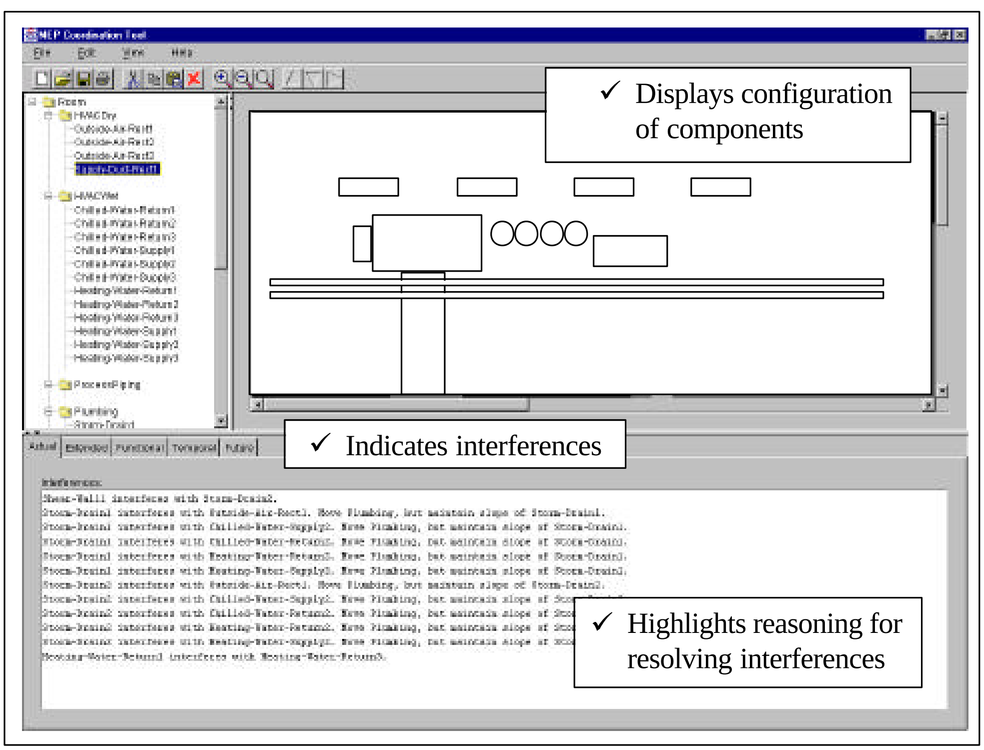


Figure 6.4 - User Interface

The user interface allows the user to view the component database in full detail. By clicking on a particular component in the component tree, an additional window appears, shown in Figure 6.5. This pop-up window gives the user specific information about the component in question. In the pop-up window of the component database, the user has the option of altering the information found in the database.

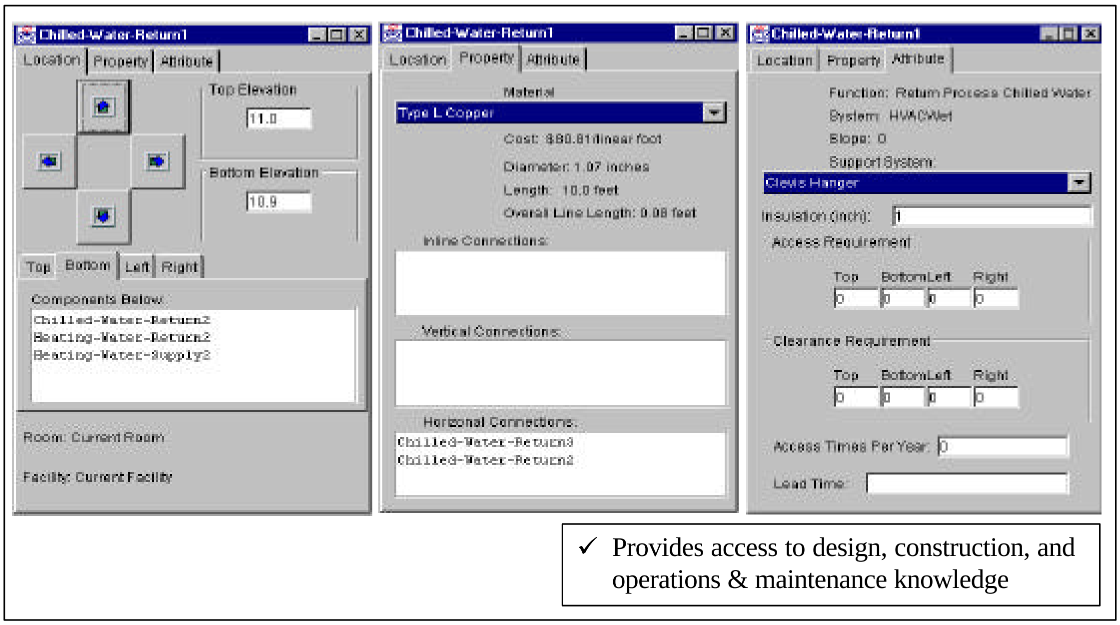


Figure 6.5 - Component database pop-up window

6.4 Limitations of the Prototype Tool

The tool is not commercial software; with the aid of an undergraduate computer-science student, it was designed and developed for research purposes and is limited in executing certain capabilities. The primary limitations are the basic structure of the user interface. Compared to commercial software such as AutoCAD^{TM} and QuickPEN^{TM}, the user interface only allows limited software links; furthermore, the links that exist support a relatively low level of data exchange between software applications. The graphical display of components used in the prototype tool is only able to support a two-dimensional rendering. As described, data transfer to VRML provides a three-dimensional visualization capability; however, movement of components is not possible in VRML.

The elementary geometric representation limits the reasoning ability of the prototype tool. As described, I designed the prototype tool to represent objects as rectilinear solids, not as they actually exist in the real world. For example, the prototype tool does not correctly represent cylindrical shapes, but uses their upper and lower bounds. A more sophisticated geometric reasoning algorithm would allow the reasoning structure developed in this research to take full advantage of the geometric reasoning capabilities. In addition, further development of the user-interface is necessary to increase user-friendliness, simultaneous access to multiple software, graphical representation, and three-dimensional rendering.

Chapter 7 describes two test cases that use the MEP coordination tool to validate the knowledge framework and reasoning structure. It also describes how the tool performs MEP coordination.

Chapter 7 – Results of Test Cases

This chapter describes two test cases performed during the validation phase of this research. The first section briefly reviews the scope and purpose for developing the prototype tool and highlights the primary limitations of the tool's capabilities. The second section introduces the test cases, including their selection criteria and testing procedure. The third section describes the exact nature of the cases and contains the raw input data and test results. The chapter concludes by analyzing the results and highlighting specific conclusions.

7.1 Using the prototype tool to validate the research results

The first objective of this research was to increase the understanding of current practice (see Chapter 2). The second objective was to develop a knowledge framework and reasoning structure to assist in MEP coordination (see Chapter 5). The third objective was to develop a computer-based tool to apply the knowledge framework, reasoning structure, and heuristics to actual projects and to validate the results of this research. The test cases described in this chapter demonstrate the capabilities of the tool and provide a means of validating the knowledge collected during the research.

As described in Chapter 6, the prototype MEP coordination tool is a JAVA™ program that applies knowledge to a 3D CAD model and provides feedback to engineers concerning several types of interferences to resolve coordination problems for MEP systems.

To begin using the tool, one must import, for each building system, electronic versions of the preliminary shop drawings prepared by separate specialty contractors. These preliminary drawings include components from each system: HVAC dry, HVAC wet, plumbing, fire protection, and electrical; together they create a composite model. The composite model also includes major structural elements and architectural features that define the facility envelope. The tool selectively applies coordination knowledge to components in the model to identify multiple types of interferences and to assist in performing MEP coordination. The output is a coordinated model that complies with constraints from each design discipline.

7.2 Purpose, criteria, and procedure for test cases

This section describes the purpose of using test cases for validation, comments on the criteria for selecting projects for test cases, and outlines the procedure for performing the test cases.

7.2.1 Purpose of test cases

First, the test cases validate the knowledge framework developed in this research. The knowledge framework contains component characteristics and attributes. One purpose of the test cases is to determine whether the framework contains the knowledge concerning each component needed to perform coordination. The completion of the test cases involves comparing the components' attributes against the indicators of good coordination (see Section 2.5.3) and when available, the actual coordination drawings. In addition, the test cases provide feedback concerning the possible need for additional attributes in the knowledge framework.

The test cases will also validate the reasoning structure, specifically its heuristics and methods. The test cases assess the ability of the reasoning structure to identify coordination problems similar to those encountered during the actual coordination process. The identification of multiple types of interferences and the feedback provided regarding these interferences assist in resolving coordination problems.

This research used two test cases. First, the Marriott hotel project, a retrospective case, indicated the extent to which the tool produced results similar to those of the current coordination process. Second, the Terman environmental engineering lab project, a prospective test case, showed how the tool used the represented knowledge to assist in decisions. This test case made the similarities and differences apparent between advice provided by the prototype tool and the current process.

7.2.2 Selection criteria for test cases

Key project characteristics provided the criteria for selecting test cases. First, I wanted to complete test cases on projects using each of the two project delivery systems that are most common in the construction industry today: design-bid-build and design-build. Using test cases from projects with different delivery systems allowed my to make observations and conclusions regarding the availability of required information. This also allowed me to identify any differences between the knowledge needed during actual coordination versus the knowledge contained in the prototype tool.

Project size was the second criterion for selecting the test cases. The limitations of the prototype tool required me to focus on small sections of larger projects. Therefore, projects with a number of congested areas that required MEP coordination were more desirable. The congested areas needed to contain a balance of MEP systems and components installed by multiple contractors in order to apply as much of the knowledge as possible. This criterion was important to allow conclusions regarding the differences between the routing and coordinating of multiple systems.

7.2.3 Procedure for test cases

I based the test case procedure on the actual coordination process, with the prototype tool replacing the SCOP. The following steps comprised the procedure for the test cases:

- obtain design drawings
- render systems and components in 3D
- import to prototype coordination tool
- perform coordination with prototype tool
- export to VRML for visualization
- highlight conclusions from test case results.

The test cases began with obtaining the design drawings for each system located in the area under consideration. Either the engineer or the contractor provided the drawings, depending on who was responsible for the design and layout before coordination. Typically, the drawings were in 1/8” scale. The HVAC drawings used two lines to represent the layout of air distribution ducts; piping was single line. The drawings give the height and width of each duct size. Pipe layouts appear as single lines with call-outs referring to the diameter and contents of each pipe. For both ductwork and pipe, there is typically no reference to the insulation required. The drawings do not indicate neither top and bottom elevations nor do they show horizontal offsets from the structure or other architectural features.

Once I obtained the drawings, I geometrically represented the system components in AutoCAD™. This involved rendering the components in 3D to scale and setting their preliminary elevations. Once I rendered all the components, the composite product model was ready to export into the prototype tool.

Exporting and importing the data for geometric representation involved the use of a third-party application, BOUNDBOX, developed specifically for this research. This application captures the upper and lower bound coordinates of each component in the composite model. It records these data points in an ASCII text file, which the prototype tool opens later.

The user then coordinates the systems using the prototype tool. First, the tool identifies the number and type of interferences. After this, the reasoning structure prioritizes the interferences and indicates a suggested sequence to resolve them (see Sections 7.3 and 7.4 for test case results). A VRML file enhanced visualization of the interferences and possible solutions.

After coordinating and rearranging all the components, I compared the results against the indicators of good coordination and, when available, the results of the actual coordination process, which appear on the contractor's shop drawings. This allowed me to analyze the results and highlight conclusions.

7.3 Marriott hotel project test case

The following section describes the test case from a Marriott hotel. It explains the reasons for the selecting this project, describes the portion of the project used, summarizes the output and results, and analyzes results from the test case.

7.3.1 Description of the project

The Marriott Corporation developed a site for a seventeen-story hotel located at the corner of Second and Folsom Streets in the South of Market district of San Francisco. This project marked Marriott's third hotel site in the City and County of San Francisco. The project includes thirteen floors of hotels rooms, set in a horseshoe pattern to provide views of San Francisco's financial district and the Bay Bridge. The first two floors include meeting spaces and dining areas. The architect allocated the top two floors of the structure for mechanical equipment and private penthouses. There are two stories below grade that include areas for parking and additional mechanical equipment.

The project used the traditional design-bid-build delivery system. The design team included the architectural firm Johnson/Braund Design Group (Seattle, WA), the structural engineering firm Watry Design Group (San Mateo, CA), and the mechanical design consultant Tower Engineering (Napa, CA). The construction team included general contractor Swinerton and Walberg (San Francisco, CA), and specialty contractors Scott Mechanical (San Leandro, CA), Cupertino Electric (Cupertino, CA), and Northstar Fire Protection (Pleasanton, CA). The estimated construction cost at the time of bid was $46 million. The active systems (mechanical, electrical, plumbing, and fire-protection) had a total estimated construction cost of $11 million. Excavation for the foundation began in June 1999 and the coordination of the active systems began in October 1999. The hotel is set to open in September 2001.

7.3.2 Selection, motivation, and project characteristics

The architect and structural engineer designed the structure. The mechanical design consultant was responsible for the design (sizing and layout) of the mechanical, electrical, plumbing, and fire-protection systems. Typically, the fire-protection specialty contractor is responsible for both design and installation of this system. For this project, Northstar Fire Protection was only responsible for fabrication and installation of the fire protection system. Scott Mechanical fabricated and installed the HVAC wet, HVAC dry, and plumbing systems. This subcontract structure made this project attractive as an example of the pure design-bid-build approach.

The physical characteristics of this project also made it appropriate for research. It contained many congested areas that included all of the active systems considered in the prototype tool. I selected a corridor at the P1 level for the test case. The corridor, located one floor below grade, provides a critical exit path for fire evacuation. It connects the employee locker room with the main stairwell. Many major mechanical rooms surround the employee locker room. The test case included the entire 62-foot length of the corridor. Figure 7.1 is a 3D rendering of the corridor.

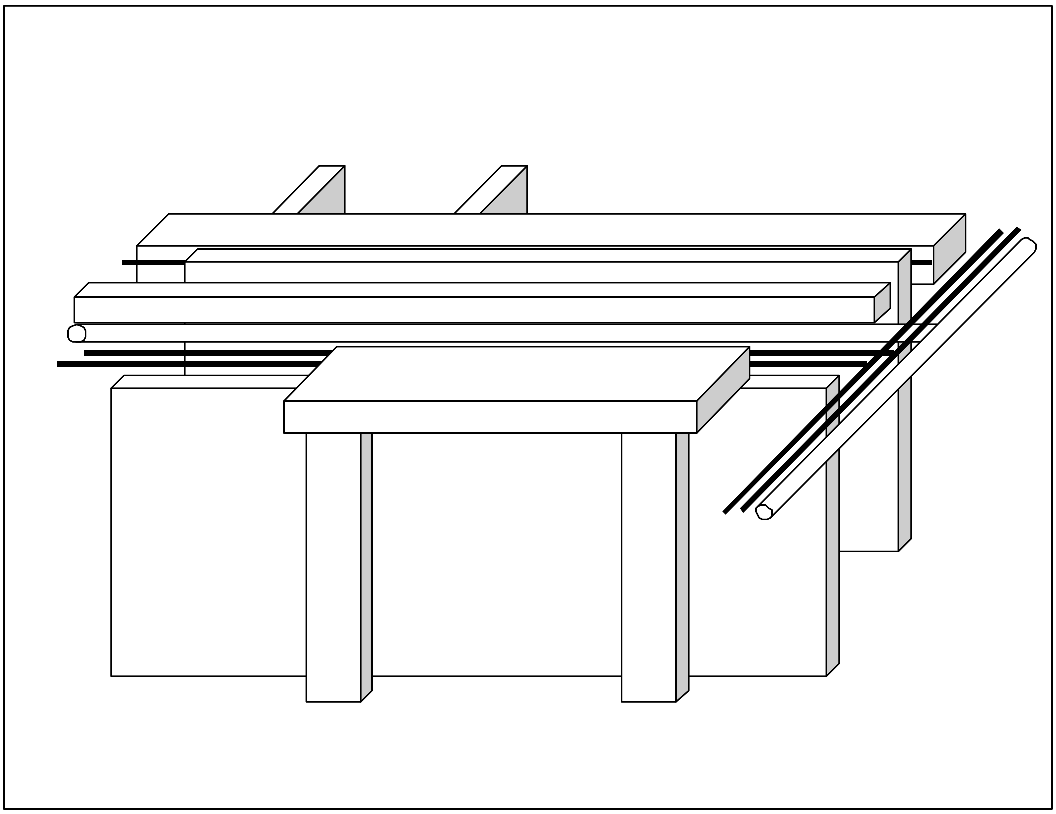


Figure 7.1 – Marriott project - exit corridor

7.3.3 Marriott test case - Output and results

The systems involved in the test case included HVAC dry, HVAC wet, plumbing, and electrical. The specialty contractors could not relocate the architectural and structural systems. Tables 7.1 and 7.2 list the systems and components in the composite model that I rendered in AutoCAD™ and imported into the prototype tool. The prototype tool determined the **Is-Connected-To** relationships found in the table using the Relationships! method described in Section 6.1.3.

Table 7.1 – MEP systems and components in the composite model

System	Component	Is-Connected-To
HVAC dry	Outside-Air-Rect1, 2, and 3	Outside-Air-Rect1 to 2 Outside-Air-Rect2 to 3
	Supply-Air-Rect1	
HVAC wet	Heating-Water-Supply1, 2, and 3	Heating-Water-Supply1 to 2 Heating-Water-Supply2 to 3
	Heating-Water-Return1, 2, and 3	Heating-Water-Return1 to 2 Heating-Water-Return2 to 3
	Chilled-Water-Supply1, 2, and 3	Chilled-Water-Supply1 to 2 Chilled-Water-Supply2 to 3
	Chilled-Water-Return1, 2, and 3	Chilled-Water-Return1 to 2 Chilled-Water-Return2 to 3
Plumbing	Storm-Drain1, 2, and 3	Storm-Drain 1 to 2 Storm-Drain 2 to 3
Electrical	Lighting-Fixture1 and 2	

Table 7.2 – Structural and architectural components in the composite model

System	Component	Is-Connected-To
Structural	Shear-Wall1, 2, and 3	Shear-Wall1 to 2 Shear-Wall2 to 3
	Column1, 2	Beam1
	Beam1	Column1 and Column 2
Architectural	Dry-Wall1, 2, and 3	Dry-Wall1 to Shear-Wall2 Dry-Wall1 to Shear-Wall3

Table 7.3 lists the interferences identified by applying the MEP coordination tool during the test case. The table also lists the relocation selected for each component to resolve the problem based on advice from the tool. Since the Marriott test case was retrospective in nature, I compared the results from the prototype with the actual coordination results.

Table 7.4 identifies and explains the differences between the results of the actual coordination process and those using the prototype tool.

Table 7.3 - MEP coordination tool tracking sheet

Move Number	Component Name	Movement	Reason for position change (Type of Interference resolving)
1	Outside-Air-Rect1	Move down below beam	Actual interference with Beam1
2	Supply-Duct1	Move up and over outside-air-rect1	Actual interference with Return-Duct1
3	Storm-Drain1	Move down	Actual interference with Outside-Air-Rect1
4	Storm-Drain2	Move down	Actual interference with Outside-Air-Rect1
5	Storm-Drain1	Move up and over outside-air-rect1	Actual interference with Chilled-Water-Supply2, Chilled-Water-Return2, Heating-Water-Supply2, and Heating-Water-Return2
6	Storm-Drain2	Move up and over outside-air-rect1	Actual interference with Chilled-Water-Supply2, Chilled-Water-Return2, Heating-Water-Supply2, and Heating-Water-Return2
7	Outside-Air-Rect2	Move Outside-air-rect2 down	Extended interference with Beam2
8	Storm-Drain1	Move down	Extended interference with Outside-Air-Rect1
9	Heating-Water-Return1	Move up	Functional interference with Heating-Water-Return2

Table 7.4 indicates that the results of the prototype tool differed from the actual coordination results when engineers redesigned, resized, or rerouted components in the actual coordination process. These differences occurred because the prototype can only indicate the ripple effects of design changes. It does not have the capability to redesign, resize, or re-route components. As will be discussed in Section 7.5.1 additional design

knowledge is necessary for the prototype tool to perform these functions.

Table 7.4 – Differences between the actual process and prototype tool results

Component Name	**System**	**Explanation for final position of components in prototype tool different from actual coordination process**
Outside-Air-rect1	HVAC dry	In the actual process, the design engineers redesigned and rerouted Outside-Air-Rect1 due to its interference with Beam1.
Supply-duct1	HVAC dry	In the actual process, the design engineers redesigned and resized Supply-Duct1 due to lack of space and its interference with Outside-Air-Rect1.
Chilled-Water-Supply1	HVAC wet	In the actual process, the design engineers rerouted Chilled-Water-Supply1outside the corridor to allow additional access space for operation and maintenance personnel.
Chilled-Water-Return1	HVAC wet	In the actual process, the design engineers rerouted Chilled-Water-Return1 outside the corridor to allow additional access space for operation and maintenance personnel.
Heating-Water-Supply1	HVAC wet	In the actual process, the design engineers rerouted Heating-Water-Supply1outside the corridor to allow additional access space for operation and maintenance.
Heating-Water-Return1	HVAC wet	In the actual process, the design engineers rerouted Heating-Water-Return1outside the corridor to allow additional access space for operation and maintenance.
Lighting-Fixture 1 and 2	Electrical	In the actual process, the design engineers relocated Lighting-Fixture1 and 2 onto corridor wall.

7.4 Terman environmental engineering lab project

The following section describes the Terman Environmental Engineering Lab project. It explains the motivation behind the selection of the project, describes the portion of the project used in the test case, summarizes the output and results from the test case, and provides an analysis of results.

7.4.1 Description of the project

The environmental engineering labs in the Department of Civil Engineering and Environmental Engineering at Stanford occupy the basement level of the Terman Engineering Center. The project involves a complete renovation of the lab facilities. This includes installation and construction of a new HVAC wet, HVAC dry, clean-dry-air, vacuum, deionized water, plumbing, and electrical system.

The University is using the design-build delivery system for the project. The project design team includes two firms: an architect, Richard Fish A.I.A., and a lab design consultant, Lab by Design, Inc. The construction team includes a general contractor, ADACON (San Jose), and three specialty contactors: Thermal Mechanical (Santa Clara), Keene Electric (Scotts Valley), and Pacific Fire Protection (San Francisco). The estimated construction cost totals $2.5 million. This figure includes all aspects of the renovation: lab casework, architectural treatment, and MEP systems. The mechanical, process piping, and plumbing costs combined are roughly $350,000, and the electrical contract is approximately $40,000.

7.4.2 Selection, motivation, and project characteristics

For this second test case, I selected a project that used the design-build delivery system. In this project, the architect and lab design consultant were responsible for only the lab aesthetics and layout. The Civil and Environmental Engineering faculty specified their needs for specific types of and desired capacities of specialty gases required for research use. The specialty contractors were responsible for the detailed design of the active systems (mechanical, electrical, and plumbing), as well as coordination, fabrication, and installation.

On the Terman Lab project, Thermal Mechanical designed and installed the HVAC wet, HVAC dry, process piping, and plumbing system. Keene Electric designed and installed the electrical system. The fire-protection system was part of the existing facility and required only minor modifications for the renovated lab space. The physical characteristics also made this project appropriate for a test case. There were many congested areas, located throughout the facility, which included all of the active systems (mechanical, electrical, and plumbing). An usual challenge for this project was the requirement to coordinate and install these systems in a facility that contained many existing systems. Therefore, the test case focused on the retrofit of the analytical lab located at the west side of the building.

The analytical lab, located two floors below grade, is the largest room in the renovated space. The existing split ceiling has approximately half the room has at a ceiling height of 9 feet, and the remaining half at a ceiling height of 14 feet. This fact complicated the coordination tremendously due to the inability to run continuous straight lines in the room. The room also contains several existing active systems to consider during the coordination process; the contract drawings did not show these systems. Figure 7.2 is a 3D rendering of the analytical lab.

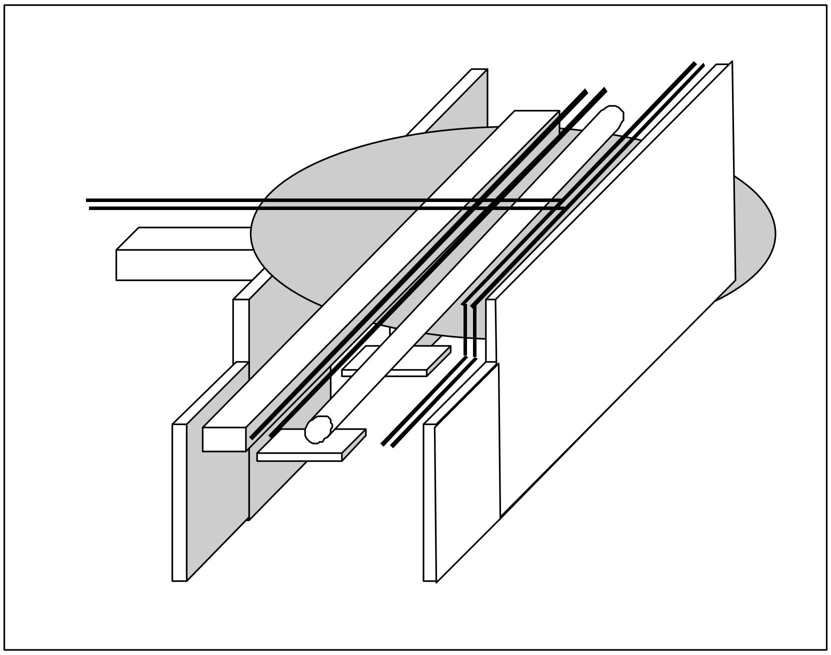


Figure 7.2 – Terman project – analytical lab

7.4.3 Terman Test Case - Output and Results

The test case included HVAC wet, HVAC dry, plumbing, and electrical systems. Tables 7.5 and 7.6 list the systems and components in the composite model that I rendered in AutoCAD™ and imported into the prototype tool. The prototype tool determined the **Is-Connected-To** relationships found in the table using the Relationships! method described in Section 6.1.3. Table 7.7 lists the interferences identified and the actions taken for resolution.

Table 7.5 – MEP systems and components in the composite model

System	Component	Is-Connected-To
HVAC dry	Supply-Duct-Rnd1, 2, 3, 4, and 5	Supply-Duct-Rnd1 to Supply-Duct-Rect1 Supply-Duct-Rnd1 to Supply-Duct-Rnd5 Supply-Duct-Rnd2 to Supply-Duct-Rnd3 Supply-Duct-Rnd2 to Air-Volume-Box2 Supply-Duct-Rnd3 to Supply-Duct-Rnd2 Supply-Duct-Rnd5 to Supply-Duct-Rnd1 Supply-Register3, 4, 5, 6, 7, 8, 9, and 10
	Return-Register1, 2, and 3	Return-Register1 to Return-Duct-Rnd2 Return-Register2 to Return-Duct-Rnd4
	Return-Duct-Rnd1, 2, 3, and 4	Return-Duct-Rnd1 to Return-Duct-Rect1 Return-Duct-Rnd2 to Return-Register1 Return-Duct-Rnd4 to Return-Register1 Return-Duct-Rnd4 to Return-Register2

	Return-Duct-Rect1 and 2	Return-Duct-Rect1 to Return-Duct-Rnd1 Return-Duct-Rect1 to Return-Duct-Rect2 Return-Duct-Rect2 to Return-Duct-Rect2
	Air-Volume-Box1 and 2	Air-Volume-Box2 to Supply-Duct-Rnd1
	Supply-Duct-Rect1	Supply-Duct-Rect1 to Supply-Duct-Rnd1
	Supply-Register1-10	(See above)
HVAC wet	Heating-Water-Supply1 and 2	Heating-Water-Supply1 to 2
	Heating-Water-Return1 and 2	Heating-Water-Supply1 to 2
Process piping	Vacuum-Line1through 10	Vacuum-Line1 to 2, 3, 4, 5, 6, 7, 8, 9, and 10
	Clean-Dry-Air1 through 10	Clean-Dry-Air1 to 2, 3, 4, 5, 6, 7, 8, 9, and 10
	Deionized-Water1, 2, and 3	Deionized-Water1 to Deionized-Water2 Deionized-Water2 to Deionized-Water3
Plumbing	Natural-Gas1 through 10	Natural-Gas1 to 2, 3, 4, 5, 6, 7, 8, 9, and 10
	Waste-Water1, 2, and 3	Waste-Water1 to Waste-Water 2 Waste-Water 2 to Waste-Water 3
Electrical	Light-Fixture1 through 14	Lighting-Fixture1 to Lighting-Fixture 9 Lighting-Fixture2 to 5, 6, and 7 Lighting-Fixture7 and 8
	Cable-Tray1 and 2	Cable-Tray1 to 2

Table 7.6 – Structural and architectural components in the composite model

System	Component	Is-Connected-To
Structural	Shear-Wall1, 2, 3, 4, and 5	N/A
	Column1	N/A
Architectural	Dry-Wall1, 2, 3, 4, and 5	N/A

Table 7.7 - MEP coordination tool tracking sheet

Move Number	Component Name	Movement	Reason for position change (Type of Interference resolving)
1	Exhaust-Register1	Move higher	Actual interference with Supply-Duct-Rnd1, Supply-Register4, and Supply Register5
2	Exhaust-Duct-Rnd1	Move higher	Actual interference with Supply-Duct-Rnd5 and Exhaust-Duct-Rnd3
3	Vaccum-Line1	Move up	Actual interference with Exhaust-Duct-Rect1 and Exhaust-Duct-Rect3
4	Natural-Gas1	Move up	Actual interference with Exhaust-

			Duct1 and Exhaust-Duct3
5	Clean-Dry-Air1	Move up	Actual interference with Exhaust-Duct1 and Exhaust-Duct3
6	Lighting-Fixture1	Move up	Actual interference with Deionized-Water2
7	Natural-Gas1	Move left	Extended interference with Shear-Wall4 (clearance requirement)
8	Lighting-Fixture2, 5, 6, and 7	Move right	Functional interference with Exhaust-Duct-Rect1
9	Cable-Tray2	Move right	Extended interference with Supply-Duct3 & 4

Since the Terman project test case was a prospective test case, I brought the results of the prototype tool to the attention of the project team. Table 7.8 lists the components where differences occurred between the project team's decisions and the suggestions made by the prototype tool.

Table 7.8 – Differences between the actual process and prototype tool results

Component Name	System	Explanation for final position of components in prototype tool different from actual coordination process
Supply-Duct-Rnd1, 2, 3, 4, and 5	HVAC Dry	In the actual process, the project team chose to reroute Supply-Duct-Rnd1, 2, 3, 4, and 5 above the lighting fixtures.
Return-Duct-Rect1 and 2	HVAC Dry	In the actual process, the project team chose to reroute Return-Duct-Rect1 and 2 above the lighting fixtures.
Natural-Gas1-10	Process Piping	In the actual process, the project team chose to mount Natural-Gas1-10 on laboratory wall.
Vacuum-Line1-10	Process Piping	In the actual process, the project team chose to mount Vacuum-Line1-10 on laboratory wall.
Clean-Dry-Air1-10	Process Piping	In the actual process, the project team chose to mount Clean-Dry-Air1-10 on laboratory wall.

Lighting-Fixture1	Electrical	In the actual process, the project team chose to move Lighting-Fixture1 forward.
Cable-Tray1 and 2	Electrical	In the actual process, the project team chose to remove and reroute Cable-Tray2 around room.

7.5 Analysis of test case results

The following section analyzes the results of both test cases. It compares the results obtained through both means of coordination: use of the prototype tool and the actual coordination process. The analysis begins by comparing the prototype results with the current process results and suggests reasons for any discrepancies. Then Section 7.5.2 discusses the object and component representation scheme used in the prototype tool and compares it with the actual coordination process. Sections 7.5.3 and 7.5.4 give conclusions regarding the completeness of the knowledge framework and reasoning structure, respectively, and their ability to assist in the coordination process. Section 7.5.5 describes specific conclusions about the prototype tool and its use for MEP coordination.

7.5.1 Comparison of prototype results to current process results

For the Marriott project, the results produced by the prototype tool were similar to the coordinated design produced by the actual coordination process. The results produced by the prototype tool for the Terman project proved to be of great assistance for the project team. As shown in the tables found in Sections 7.3.3 and 7.4.3, there were few instances where the results from the actual coordination process differed from those of the prototype tool.

There are two primary reasons as to why the results differed between the actual coordination process and the prototype tool. First, for several components, resizing was necessary during the actual process. Second, the prototype tool had insufficient knowledge regarding detailed design and was unable to perform design calculations. These two factors were responsible for the differences between the prototype tool results and actual coordination results. I discuss the exact differences found in each test case below.

In the Marriott project test case, the primary differences in the solutions included the resizing of the storm drain line, redesign of the outside air duct, and resizing of the supply air duct. The project engineers resized the storm drain to increase flow capacity during the actual coordination process. The engineers redesign was not a result of a coordination conflict, but did affect the positioning of the storm drain line. The actual coordination process identified an actual interference between the outside air duct and the drop-cap beam. The prototype tool did identify the interference, but resolved it by relocating the outside air duct and supply air duct. The actual coordination process resolved the problem by redesigning the outside air duct. This affected the performance of the supply air duct that the engineers also redesigned. The reasoning structure of the prototype tool was not sophisticated enough to know how the redesign of the outside air duct would affect the performance of the supply duct.

In the Terman project, the primary differences between the actual coordination results and prototype tool results included the rerouting of the exhaust air duct and the cable tray. The prototype tool identified the actual interferences between the exhaust air ducts and the clean-dry-air line, vacuum line, and gas line, as well as the functional interference with the lighting fixtures. The prototype tool resolved the coordination problem by relocating the clean dry air, vacuum, and natural gas lines to a higher elevation. When I proposed this suggestion to the project team, they stated that they would resolve the problem by rerouting the exhaust up and over the clean-dry-air, vacuum, and gas lines. They proposed to create an upward saddle in the duct to avoid relocating the clean-dry-air, vacuum, and gas lines. Another difference occurred with the rerouting of the cable tray. The prototype tool detected the functional interference between the cable tray and supply air duct. The solution recommended by the prototype tool was to relocate the cable tray. The prototype tool did not have the knowledge regarding the location of the telephone service outlets, because they had not been located at the time of the test case; therefore, it could not relocate the cable tray properly.

7.5.2 Object and component representation

The object representation scheme of grouping components, the use of continuous lines versus in-line connections, and the use of topological relationships worked well in the prototype tool. The grouping of components, described in Section 5.2.1 proved to be valuable in reducing the number of components in the prototype tool. The use of continuous lines versus in-line connections for longer lines also reduced the number of components; however, this limited the ability to apply construction knowledge to the installation process. Therefore, in rendering the individual systems for integration of the composite product model, I used in-line connections only in locations where they were essential. The topological relationships determined by the reasoning structure, such as Is-Connected-To and Is-Located-Above, also proved to be a necessary feature in performing coordination within the prototype tool.

The prototype tool's geometric representation scheme limited the ability to optimize the placement of the components during coordination in two specific instances. The first instance was sloped lines. These lines require special geometric attention that the current prototype tool cannot provide. This is due to the representation scheme used by the prototype tool for objects and components as rectilinear solids, which limits the relocation of components around sloped lines. This limitation occurs from representing the sloped line as a rectilinear prism shape with the upper and lower bounds indicating the extreme top elevation and extreme lower elevation, respectively. During the actual coordination process, this constraint does not exist. The second instance in which the geometric representation scheme limited the ability to optimize the placement of components dealt with individual component support systems. The prototype tool does not give enough attention to either space requirements or locations for support systems. Therefore, just as with sloped lines, this limits the placement of components as close to each other as in the actual coordination process.

7.5.3 Knowledge Framework

For the most part, the knowledge framework contained the knowledge necessary to perform coordination. In both of the test cases, the coordinated design (actual and test cases) followed the indicators of good coordination. The knowledge structure contained the necessary component attributes; however, the reasoning structure did not always fully use the attributes in the prototype tool. I believe future researchers need to enhance the knowledge framework to include additional characteristics and attributes regarding connections. The lack of this knowledge was obvious while performing coordination with the prototype tool. Related to this was the lack of knowledge regarding routing for specific systems. I found that I underrepresented routing knowledge in the knowledge framework and should be included in further development. Despite the deficiencies, the knowledge contained sufficient component attributes to demonstrate the effectiveness of the tool.

7.5.4 Reasoning Structure

The reasoning structure was able to identify all the interferences identified during the actual coordination process. In fact, it went well beyond standard practice for determining interferences. A positive aspect of this was that the reasoning structure made it possible to identify all interferences in the composite product model. There were no interferences from the actual process not identified by the tool. However, it was not possible to resolve all interferences without creating further interferences in other areas of the composite model. When I pointed out this fact to the construction teams involved in both projects, they responded that field installation crews would be able to resolve many of these interferences identified by the prototype tool by adding extra connections during installation. Therefore, these additional interferences were not a concern.

Note that the prototype tool 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 technical data at all. Upon completion of the coordination process, it is certain that they must resolve all interferences, or else deal with the interferences during installation and construction. Therefore, I feel that the priority comparison system built into the reasoning structure was more important for resolving interferences with the prototype tool than in the actual coordination process where contractors sometimes make decisions without technical rationale.

7.5.5 Overall conclusions from test cases

The test cases indicated that the structure and content of the knowledge framework was adequate to prove the concept. The component attributes in the knowledge framework provided a knowledge base that the reasoning structure used to provide recommendations for resolving coordination problems. The results also indicated that such a tool is able to provide valuable assistance for MEP coordination and is possible for use on future projects.

The test cases also revealed two primary deficiencies of the tool. First, the tool should provide more information about the reasoning used to resolve interferences. The tool needs to provide more clarification regarding the rationale it uses to make suggestions. Since the prototype tool symbolically represents knowledge in the tool, the raw knowledge is not available to the user. The users focus on what they can visualize, as they do in the actual coordination process. The prototype tool needs a better means to provide this additional information, which contractors communicated verbally during the coordination meetings.

Second, users require increased visualization capabilities. This need stems from the inherent nature of MEP coordination. Components actually exist in a 3D world. In the actual coordination process, contractors perform coordination on flat 2D drawings. The capability to integrate a three-dimensional geometric representation of components with reasoning proved to be extremely valuable in identifying interferences other than physical clashes. Extended interferences were much easier to visualize in the 3D environment and the tool was able to provide additional information regarding functional, temporal, and future interferences. This is not available on coordination drawings.

The test cases not only validated the knowledge framework and reasoning structure, they were also useful in revealing research contributions and providing recommendations to industry. Chapter 8 will discuss each of the major contributions from this research and will describe recommendations for future research and practice.

Chapter 8 - Contributions and Recommendations

8.1 Contributions

The MEP coordination process is a critical step in the planning and design of complex buildings and industrial plants. As described in Chapter 2, three primary problems exist with the current process:

- it is highly fragmented because there is a lack of shared knowledge among those involved
- there is a wide variation in the level of technology used throughout the process
- the process does not produce a facility model for use during operation and maintenance.

Chapter 1 posed this question: "How can knowledge of MEP systems, derived from all phases of a project lifecycle, a) be represented to reflect the knowledge required for MEP coordination? b) be structured to provide reasoning capabilities to identify and assist in resolving coordination problems? c) be applied to demonstrate use of computer technology to assist with MEP coordination?" This question helped me to meet the objectives and led to the three primary contributions of this research:

- I increased the understanding of current practice and problems associated with coordinating building systems.
- I developed a knowledge framework and reasoning structure that uses the knowledge required for MEP coordination.
- I demonstrated the technical feasibility of developing a tool to assist in performing MEP coordination.

The following sections summarize the point of departure and describe the major elements for each of these contributions.

8.1.1 Increased understanding of the current practice for MEP coordination

Before this research, the literature presented very limited descriptions of MEP coordination. Most of the papers or articles on the subject only acknowledged the problems and difficulties associated with the process. My first contribution in this research is the increased understanding of the current work process used to coordinate MEP systems on complex building projects - the Sequential Comparison Overlay Process (SCOP). The four main aspects of this contribution are describing the process, identifying problems, distinguishing the multiple types of interferences, and defining the indicators of good coordination.

I began this research with interviews of many experts who hold a deep knowledge of each system. These interviews included meeting with all parties involved in the decision-making process and collecting information regarding their objectives, their priorities, and method of analysis. As described in Chapter 4, I also observed numerous MEP coordination efforts on a variety of projects both in design and in construction. My description of current practice covers each step involved in the SCOP, from drafting conceptual drawings to completing coordinated drawings. It also identifies the reasons why the current process exists, describes the people and organizations involved, and examines the industry conditions and contract provisions that perpetuate the current process.

After completing my description of the current process, I was able to identify and describe the common problems associated with this critical and complex activity. I described problems with specific systems and components and identified cost and schedule implications of poorly coordinated systems. I identified specific portions of facilities that require special attention during the MEP coordination process, such as corridors and ceiling spaces. I highlighted the lack of resources – in particular people with the required deep knowledge of the systems – and the lack of consideration for the entire lifecycle of the facility as important problems. In addition, I investigated the current use of information technology for MEP systems in buildings and explored the limitations of this technology in this application.

From my understanding of the current process, I was able to distinguish the differences between the multiple types of interferences that arise during SCOP. I classified these interferences into the following categories: actual, extended, functional, temporal, and future. This is a significant contribution because prior to this research only actual and extended interferences were considered germane to MEP coordination. I demonstrated the necessity of considering functional, temporal, and future interferences that previously prior research ignored during the coordination process.

Finally, as a part of describing current practice, I identified factors that coordination experts consider the most important indicators of good coordination and classified them by project phase: design, construction, operations, and maintenance. For example, designers are concerned with following a grid pattern in routing, centralizing similar systems, and routing similar systems at the same elevation. Constructors emphasize meeting cost and schedule estimates, considering the installation sequence, and minimizing the number of fittings and connections. Operations and maintenance personnel are concerned with reserving space for access to key components and reserving adequate space for future expansion. Before these classifications, it was difficult for the coordination participants to understand each other's individual objectives. These classifications now facilitate the coordination process by helping to clarify the objectives of coordination for each of the participants.

This greater understanding of current practice helps to overcome the lack of prior research regarding the process and knowledge required for MEP coordination. The prior view of MEP coordination was solely the arrangement of multiple building systems components, within the constraints of architecture, structure, and system performance. With this increased understanding, I provided a basis for helping industry improve work process for MEP coordination by expanding the current view to include construction, operations, and maintenance issues during MEP coordination. Therefore, this knowledge of the current process provided an essential point of departure for the remainder of this research.

8.1.2 Increased understanding of the knowledge required for MEP coordination

Current practice involves inconsistent use of fragmented knowledge to perform MEP coordination. Moreover, as mentioned previously, there was no published background about the knowledge required for MEP coordination. Therefore, my second contribution is in the increased understanding of the knowledge required to perform coordination. In this research, I collected, analyzed, and represented the knowledge required to perform MEP coordination in a knowledge framework, and demonstrated how this knowledge can be applied to assist in MEP coordination in a reasoning structure. My contributions with respect to knowledge frameworks consist of classifying knowledge by design, construction, operations, and maintenance; determining appropriate object attributes; and identifying interferences using the object attributes. My contributions regarding the reasoning structure involved formulating heuristics, defining solution classes, and developing logic for heuristic matches. I discuss each in further detail below.

Knowledge frameworks previously used for design and construction typically dealt with conceptual rather than detailed design. For example, Fischer's COKE model captured and represented design-relevant constructibility knowledge in the design phase to help designers check for constructibility issues during early concrete design [Fischer 97]. Chinowsky's CADDIE Project used knowledge to capture multiple constraints and assisted architects in developing conceptual design diagrams. The knowledge for CADDIE focused on a limited number of domains and space adjacencies [Chinowsky 91]. My research identified the knowledge required for multi-trade coordination from multiple experts about multiple systems and project phases, and considered design, construction, operations, and maintenance.

On a more fundamental level, the knowledge framework contains component attributes that integrate knowledge about design criteria and intent, construction, operations, and maintenance (see Section 5.1). This framework includes knowledge commonly held by the disciplines most frequently associated with MEP coordination: mechanical, electrical, plumbing, and fire protection. The knowledge represented begins with the building systems involved in the coordination process. Following the building systems, I represented the components for each of the other systems involved, such as fire sprinkler supply lines and HVAC supply ducts. Finally, specific attributes related to each component are stored in the knowledge framework. Examples of the types of attributes include component function, material type, required installation space, and access frequency. This contribution is significant because I was able to tailor the knowledge framework to focus directly on what was required to perform MEP coordination for each building system.

Before this research, it was difficult to determine why certain interferences arose. This contribution is significant because I showed how to use component attributes to identify and resolve interferences. For example, the reasoning structure classifies an interference that includes the component attribute insulation or support system as an actual interference. The reasoning structure classifies an interference that includes any of the following component attributes: installation space, installation frequency, or lead-time as a temporal interference.

Related to the reasoning structure, I formalized the heuristics that govern the resolution for coordination problems. The heuristics incorporate the indicators of good coordination by categorizing possible solutions into the following classes -- detailing, layout, positioning, application, and scheduling. These solution classes use heuristics to assist in resolving interferences identified during the MEP coordination process. Lastly, I developed logic to make heuristic matches possible. This is critical because these heuristic matches allow the reasoning structure to provide feedback regarding coordination problems.

8.1.3 Demonstrated the technical feasibility of developing a tool for MEP coordination

Developing a computer-based tool to assist in MEP coordination is an important step towards using information technology to assist in planning the construction of MEP systems. Therefore, my third contribution is demonstrating the technical feasibility of developing a tool for MEP coordination. This research shows that it is possible to integrate MEP systems in one common CAD model, select and represent pertinent component attributes from each project phase, and apply knowledge to identify problems.

First, I demonstrated that it is possible to integrate the building systems into one common CAD model. Before this research, design engineers have historically represented building systems in 2D on flat drawings. When designers represented components three-dimensionally, they became too complicated to integrate into one common CAD model. The level of geometric representation used in this research allows reasoning to take place while maintaining a graphical representation of building systems components.

Next, I demonstrated how selected component attributes related to each project phase -- design, construction, operations, and maintenance –- could be integrated to encompass the entire project life cycle and assist in MEP coordination. The prototype tool developed in this research focuses on resolving conflicts commonly found during the MEP coordination process. It improves the process by integrating design, construction, operations, and maintenance knowledge to produce designs that better satisfy these diverse criteria. The capabilities of the prototype tool include:

- integration of MEP systems into one common CAD model
- application of multiple disciplines' knowledge
- integration of design, construction, and operations knowledge to aid coordinating various MEP systems

Lastly, I demonstrated how a computer tool is able to apply knowledge from multiple disciplines to identify problems, first by identifying multiple types of interferences, and then by providing advice for resolving coordination problems. Previous research demonstrated successful use of knowledge from other areas in computer tools, such as Fischer's work in constructibility analysis of concrete structures. Fischer's COKE model is the closest available tool that attempts to address a problem similar to MEP coordination. It assisted designers in checking the constructibility of conceptual concrete design using criteria related to concrete formwork. COKE assists designers in checking the contractors' ability to use different types of concrete formwork. The COKE model focused on conceptual design for the structural discipline and provided very useful background for this research by demonstrating the feasibility of using a symbolic model for vertical integration.

The results from this research will assist future researchers in integrating knowledge of multiple disciplines in CAD systems. In this research, I showed how future researchers can apply MEP knowledge to product models to assist in multi-disciplinary coordination. Section 8.3 discusses the use of the prototype tool as a basis for redesigning the work process and improving current practice.

8.2 Recommendations for future research

The results of this research indicate excellent potential for continued investigation of knowledge related to MEP systems. I believe the priority for future research should include:

- addressing the limitations of the prototype tool developed in this research
- developing ways to estimate the building volume required for operation and maintenance of MEP systems
- adding capability for increasing use of modularization and pre-fabrication of MEP systems, along with the architectural features and the structural elements of buildings
- adding capability to analyze the impact of coordination on schedule and cost
- considering MEP coordination in spaces other than in buildings.

The following sections discuss each of these possibilities for future research, address why each of these are a logical extension, and consider how others may use this research as a foundation for future research.

8.2.1 Re-routing and Re-sizing knowledge extension

Often installers must make decisions in the field that affect the design of a system, i.e. increasing or decreasing an HVAC dust size to meet a clearance. However, these decisions may affect the design performance of a system, for example the static pressure and airflow in the duct. Currently, the prototype tool does not have the knowledge to re-size or re-route MEP system. 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 is a useful and logical step. This would enable MEP designers and constructors to expedite coordination efforts even further than possible with the prototype tool and may even allow architects to create more usable space within the building envelope.

8.2.2 Optimization of space and estimating space needs for MEP systems

Increased applications of heuristics in computer tools can further automate the coordination process. Currently, the prototype tool only provides recommendations for arranging the building system components to avoid several types of interferences. Optimizing the space available is the next logical extension. This could enable architects to reduce story heights and building cost. This extension may even allow architects and constructors to create more usable space within the building envelope.

From what I 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, based on the indicators of good coordination. For example, future researchers could expand each project phase – design, construction, operations, and maintenance – to include optimization algorithms. This would allow planning teams to use the extended MEP tool in considering the implications of decisions made during schematic design on all building systems.

8.2.3 Using modularization to improve MEP coordination

Modularization to improve MEP coordination is another logical extension of this research. Currently, the construction process for building systems involves delivering individual components of the systems to construction sites. Construction crews reserve space for material lay down. This space takes up a considerable amount of the construction site. Workers assemble and install components together in the field. Minimizing these steps requires maximum use of pre-fabrication and modular sections.

From what I have learned in this research, modularization would require collecting additional knowledge regarding modularization and pre-fabrication of building systems and extending the knowledge framework and reasoning structure. For example, future researchers could investigate fabrication and installation of HVAC ductwork together rather than as two different steps in the project cycle. This research requires considering the fabrication parameters of size and shape of the duct as well as construction parameters of the installation sequence to increase the use of modular and pre-fabricated components.

8.2.4 Coordination of impacts on cost and schedule

Investigation of the multiple ways that coordination problems affect construction estimates and installation schedules is an ideal extension for future research because these additional capabilities would allow designers and specialty contractors to consider the cost and schedule impact of problems. I recommend extending the knowledge base to include historical cost data and construction schedule integration. I also recommend expanding the heuristics to included cost and schedule knowledge that enables the reasoning structure to calculate the ripple effects of changes.

8.2.5 Coordination in spaces other than buildings

The current knowledge domain only considers building systems - mechanical, electrical, and plumbing systems -- located in buildings. However, many projects require coordination in spaces other than the interior of buildings and industrial plants. Utility corridors are such spaces that cause frequent coordination problems. These corridors, located underground, beneath streets, and in concrete structures (such as bridges) require special attention for coordinating MEP systems. Extending the research in this direction may be most rewarding due to its immediate potential benefits.

Proceeding with this research would require expanding the knowledge domain to include the additional components and lines found in these spaces, such as high-pressure gas lines and fiber-optic cables. Researchers would need to acquire, represent, and apply similar coordination knowledge acquired in a reasoning structure.

8.3 Recommendations for Practice

This research also results in important recommendations to improve practice. These include the full development of the prototype tool and a revised work process. The following sections discuss recommended actions to further develop and implement the prototype tool for MEP coordination.

8.3.1 Full development of tool

The increasing capability of available hardware and software offers an excellent potential to develop a tool for MEP coordination, which would include the full range of capabilities described in Chapter 6. However, realizing the major potential benefits discussed above first requires additional steps to fully develop the tool for MEP coordination.
The major tasks involved in full development are adding a more sophisticated geometric reasoning algorithm, implementing JAVA 3D™ for visualization, adding links to 4D tools,

adding capability for output to AutoCAD™, and pursuing knowledge acquisition and representation. To execute these tasks and to improve programming standards for the tool would require a commercial development team. Multiple organizations are required to resolve problems with CAD data transfer, in which software suppliers such as Bentley Systems, Inc. and Autodesk Corporation would be key players.

8.3.2 Revised work process using the tool

In addition to fully developing the tool, many changes are necessary for its effective implementation. This involves implementing a revised work process that recognizes the constraints of current industry organization by allowing separate and individual designs of building systems by specialty contractors but also takes advantage of the capability provided by a computer tool similar to the prototype tool in this research.

A possible revised process, as shown in Figure 8.1, would start with separate CAD files routing each of the systems. Specialty contractors prepare these. The coordination tool would combine and analyze these files in a 3D CAD model to identify interferences with different types of design criteria. Revisions to the CAD model would capture the decisions resolving these problems. The tool would then produce separate drawings for fabrication and installation of each system.

There are challenges to creating a revised work process for MEP coordination, but it also creates an opportunity to improve project performance. As stated above, this new process must fit the existing industry structure of fragmented design by specialty consultants and contractors. It must also consider the key knowledge of experts regarding each type of system. Properly designed, a revised work process will allow tailored use of rapidly advancing computing capabilities to provide advice based on this expertise.

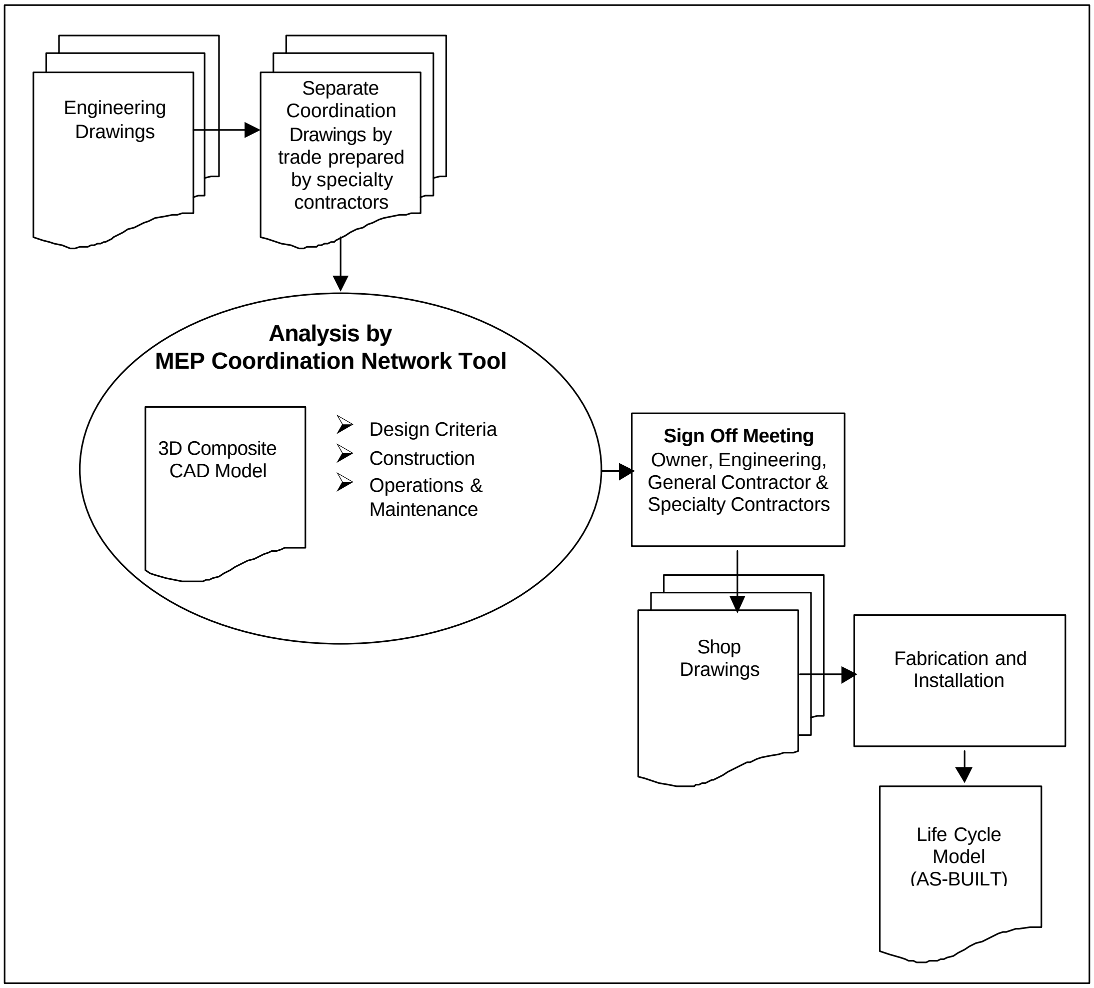


Figure 8.1 - MEP coordination using tool

These changes must begin with incentives for design consultants to design in 3D CAD and to make electronic files available to specialty contractors for coordination purposes. Incentives are also needed for specialty contractors to use common CAD design software. Currently, these contractors use tailored applications that are not compatible. One contractor should be responsible for management of the coordination tool – most likely the general contractor. Overall, incentives for the project team include reduced meeting time and coordination schedules, electronically facilitated coordination, and the ability to provide a detailed as-built drawing of the facility upon completion of the project.

8.4 Significance and benefits of the research

The current conditions in the design and construction industry drive current practice for MEP coordination and create an opportunity to improve. The current practice for MEP coordination is slow and expensive. Now completed by manual means, MEP coordination requires considerable time from scarce experts who have specialized knowledge about the design, construction, operation and maintenance of these systems. The current work process offers major opportunities to improve. This thesis has significant benefits for both researchers and industry professionals seeking this improvement.

8.4.1 Significance and benefits for future researchers

For researchers, this thesis describes how they can integrate knowledge with 3D CAD. It also uses knowledge integration and object representation to address previous research problems of linking knowledge and CAD objects. The representation in this research allows knowledge integration by use of symbolic modeling. The research encourages the use of object-orientated-programming (OOP) technology and the adoption of standard object attributes for building systems. The development of the knowledge framework as well as the methodology used to acquire and represent knowledge demonstrates how to integrate design, construction, operations, and maintenance knowledge in a general format that is useable by a reasoning structure to assist in solving coordination problems.

8.4.2 Significance and benefits for industry

Industry professionals recognize the need to use information technology and for a revised MEP coordination work process. This research provides a foundation for developing the equivalent of a plant design model for buildings – a major potential advantage for facility management, operation and maintenance. A revised work process based on this model would implement a commercial version of the prototype software developed during this research. The research demonstrates that an MEP coordination tool, similar to one developed in this research, will result in faster, better, and less costly MEP coordination. These changes will enable engineers, designers, and specialty contractors to better achieve project objectives, in addition to allowing them to apply knowledge and thus improve vertical integration.

Appendix A - Glossary of Terms

BOD	Basis of Design (BOD); Guidelines developed by the engineering design consultant that delineate the user specification and requirements for specific building systems.
Codes	The content of computer programs that run the model.
Commissioning	Process in which the installed system undergoes testing to ensure proper functioning of system and consistent and satisfactory quality of system outputs.
Conceptual design	A set of sketches containing notations about how occupants will use spaces, approximate square footage, ceiling heights, etc.
Control knowledge structure	A knowledge database that governs how the product model processes inputs.
Coordination drawings	Drawings provided by each trade they overlay in coordination meetings.
Database	A library of information stored in the computer/computer model.
Design assist	An environment in which computer programs can share and exchange data automatically (without translation or human intervention), regardless of the type of software or where the data may be residing.
Detailed design	A set of drawings which contain details and exact locations of all major components to be located in the facility.
Detailing	Indicating information and details of the system's components such as pipe layout and size on CAD drawings.
Diagrammatic drawings	Preliminary line drawings showing plan and elevation views of pipe and/or ductwork layout, such as riser diagrams and wiring diagrams.

Domain knowledge	The knowledge specific to the field which defines the problem – knowledge which has been elicited from one or more experts.
Final submittal drawings	Final set of detailed drawings submitted by each trade's subcontractor to the general contractor for engineer/owner's approval and coordination meetings.
Hard interference	The physical interference of two or more objects in a product model.
IDEF model	Integrated Definition for Modeling Language (IDEF) model is a process-flow diagram for a product model such as this one. It illustrates the inputs that are processed by the model, the control/model that govern and constrain the process, the methods that it uses to process the inputs, and the outputs that are inputs transformed by the product model.
Interoperability	An environment in which computer programs can share and exchange data automatically (without translation or human intervention), regardless of the type of software or where the data may be residing.
Knowledge base	The core rules and data that make up the domain knowledge.
Methods!	A series of procedures that are inherited by an object.
Model-based expert system	A model of a device based on knowledge on the structure and behavior of the device.
Object hierarchy	A tree diagram showing each object's relationships with other objects, methods, attributes, and predecessors.
Physical Interference	Spatial conflict among system components where the components run into each other.
Priority comparison system	Systems which certain rules or user-input priorities determine which objects hold more importance than others.
Procedural knowledge structure	The algorithms that are concerned with the manipulation of the knowledge in the search process.

Product (CAD) model	A pictorial representation of an object.
Rule-based expert system	A series of production rules based on human expertise.
Schematic design	Drawings produced by the architect which include plot plan, building elevations and sections. Drawings address program goals and objectives.
Shop drawings/Fabrication drawings	Detailed drawings from system suppliers/vendors showing plan and elevation views of layout, equipment/ device/ component locations, component size and material details, connection details, mounting details, construction materials and methods, and installation instructions.
Shop fabrication	Manufacturing and/or assembly of products in off-site factories/warehouses.
SMACNA	Sheet Metal and Air Conditioning Contractors National Association.
Soft interference	The interference of one object with another objects HALO.
Spatial incompatibility	The incorrect positioning of two objects next to each other.
Symbolic model	Object-oriented model in which each object is assigned values and attributes.

Appendix B – Results of Industry advisory group meetings

The industry advisory group (IAG) identified in following table formed a key part of the research team for this project. Members of this group are involved in coordination-intensive projects and see the need to improve coordination processes. The designers and contractors forming the group provided access to experts and projects during the time of coordination activities to allowed data collection. Also found this section are meeting minutes held with the research.

Industry Advisory Group

IAG group member	Firm	Expertise and input
Dennis Antweiler	Cascade Controls	control system design and coordination
Vic Critchfield	CMI	HVAC system design and coordination
Rudy Bergthold	Cupertino Electric	electrical design and coordination
Greg Chauman, Bill Russell	Vance Brown	MEP coordination, general contractor
Andy Meade	DPR Construction	MEP coordination, general contractor
Mark Belgarde, Todd See	Flack + Kurtz	MEP systems engineering and design
Marc Saphire	Hathaway	MEP coordination, general contractor
Richard Kirchner	Hawley, Peterson, Snyder	architectural design, MEP coordination
May Hayashi	Kinetics Systems	design and coordination, process pipe
Mike Anderson, Mike Piotrowski	Rudolph & Sletten	MEP coordination, general contractor
Steve Caporale	Sasco Electric	electrical design and coordination
Logman Ma, Mike Rowe, Tad Smith	Scott Mechanical	mechanical coordination
Charlie Kuffner, David Green	Swinerton & Walberg	MEP coordination, general contractor
John Mack, Laurie Seibert	Therma	HVAC design and coordination
Al Sanchez	Alfred Sanchez, Inc.	independent MEP coordination
Galen Hobart, John Hulin John Loguzzo	Superior Fire Protection	design and coordination of fire protection

First meeting of the Industry Advisory Group (11/5/97)

The objectives for the first meeting of the advisory group for MEP research were to better define current practices and problems of MEP coordination, comment on planned research approaches, and identify information sources. 18 members attended. The major topics of discussion were need and current practice for MEP coordination, information requirements for types of systems, options for the research product, and information sources.

Need for MEP coordination and current practice

The amount of MEP coordination activities required by the contractors depends highly on the building volume available for routing MEP systems and the completeness and quality of the design. The greatest value of a coordination tool is during early design. Used then, the tool would allow viewing the big picture, with details added later. Specialty contractors often bid fixed price with 20% design.

There is great need for an automated way to cut sections through congested areas in buildings. Adding the Z coordinate to existing drawings is a further major need. It is desirable to give everything 3D attributes and then take "MRI" scans anywhere in the system.

Use of different levels of technology by specialty contractors increases the difficulty of coordination. Light tables, although they may seem antiquated, are very useful problem solving tools in MEP coordination. The light table allows many people to gather around and discuss the problem at hand. CAD is used at the higher end of MEP coordination. The value of CAD is that all the trades work can be integrated into one drawing. However, computer hardware becomes a limiting factor with very complex projects; it is too slow in processing large models. The main problem with CAD is that not all trades work in CAD and many of the contractors who do work in CAD use different levels of detail and technology. The degree of CAD use also varies for type of work. However, more and more owners are requiring that CAD drawings be submitted as as-builts at the close-out of a job.

Engineers for some high-tech projects have provided 3D CAD models with the intent of eliminating the need for coordination. As an example, the design engineer provided a 3D model for a large biotech project. The model was actually used as a space management tool by the specialty contractors. In order to build the job, the process piping contractor produced spool sheets individually for prefabrication. The 3D model was not helpful in this regard.

Previously, contractors were just installers. More and more they are becoming the Engineer-of-Record. Engineers are focusing on consulting and performing less design. The greater the amount of information included in a coordination tool, the less time and money will be spent on coordination issues. There is also a need for better 3D-CAD systems which integrate engineering, detailing, and field experience. In current practice designs are drawn 2-3 times before actual fabrication.

Detailing is helpful for some trades. For others, it is mainly required for liability reasons (to download responsibility to contractors.) Craft experience is necessary to produce high quality construction drawings. Some think that detailing is a show and tell for clients and is not useful to the contractor. An electrical contractor indicates that their success with high-tech facilities is from early detailing.

A typical approach for MEP coordination calls for the specialty contractors to resolve problems first. The general contractor steps in when cost changes result from the coordination process. Much negotiation results with cost as a governing criterion. Redesign of selected systems is the last resort in a problem solution.

Additional rules are needed to govern the coordination process. Redesign of systems is required if no solution results from the coordination process. One example of this involves sheet metal (HVAC Dry) and fire protection. Designers of fire protection systems prefer to route main lines higher and 1-1/4" branch lines lower to allow acceptable coverage by the sprinkler heads. Ductwork competes for the same space, however, diffuser locations are somewhat flexible. Furthermore, designers of electrical systems desire to route raceway as high as possible while limiting the number of bends in the conduit. Another example is the location of the Tele/data lines. For maintenance access, these lines should be routed about 6"-12" above T-bar ceiling.

Information requirements for specific types of systems and operations

During discussions in the meeting, the attendees offered the comments regarding each of the major systems involved in MEP coordination. These included structural, signal/communication, electrical, plumbing, process pipe, mechanical, and fire protection. The comments were incorporated into the listing of coordination inputs and issues.

Important considerations that apply to all systems during the coordination process identified in the meeting included code constraints, required slope for gravity drain lines, and the desire for all disciplines to route systems high and tight and therefore reduce cost and need for seismic bracing.

The area around the building core typically presents a major coordination challenge. SMACNA guidelines are used for bracing in all types of systems except fire sprinkler, which is covered by NFPA 13. Complete detailing of the system is necessary to provide space for flanges, thermal expansion, and other variations from normal configuration. Catwalks also require coordination, if they remain in the design after value engineering. Lighting fixtures may present coordination problems because of required location and variable depth. Many changes in local codes influence system design and routing, i.e. plastic pipe is not allowed in San Francisco. There are also many codes constraints regarding system routing, e.g., UBC 94 & 97 ed., NEC, ADA, CA Title 24.

The installation sequence changes somewhat by type of project. The sequence may also change for different parts of the building. Both space allocation and installation sequence are often determined by who gets there first. Cost to change is frequently the primary criteria for resolution of interferences.

Maintenance considerations are becoming more important as buildings become more high-tech. Examples of necessary space reservations include access to control valves, access to dampers for balancing. Space allocation should also consider likely future modification and expansion.

Options for the horizontal integration tool

The attendees discussed whether the planned research should focus on improving the coordination process in a project that uses design-bid-build or design-build. The current process in both types of contracts lacks a consistent degree of effective MEP coordination. There was general consensus that assistance earlier in the project would add greater value. One option discussed for the research product was a space management tool to be used as a mechanism to flag violations. The tool may change by type of project and location in the building.

The attendees indicated that a tool to reserve space for the various trades would be very helpful. This could be used during the preliminary design of MEP systems or during the MEP coordination process. In addition, the tool should provide for setting aside clearances (halos) that specialty contractors must adhere to during detailing and installation.

Other possible features of an integration tool for coordination suggested at the meeting were capability for problem identification and support for resolution, support for system detailing, ability to transfer data over the web, ability to estimate the space needed for MEP systems during very early design phases, ability to add the third dimension to 2D CAD files, support for RFI submittal and response, and production of as-built drawings.

Some attendees stated that the scope of the research is too large. They suggested starting with a simple model and testing before moving on to larger and more complex facilities.

Second meeting of the Industry Advisory Group (1/22/98)

The objectives for this second meeting of the Industry Advisory Group for the CIFE research project concerning MEP coordination were to report findings to date on the project, describe plans for future activities focused on developing a prototype tool for MEP coordination, and obtain comments and input from the advisory group concerning the findings and plans. 8 members attended.

Research activities since first meeting

Major activities since the first meeting of the industry advisory group included collecting information concerning MEP coordination on an example project, conducting interviews concerning MEP coordination by two general contractors and a specialty contractor, describing the process for MEP coordination, analyzing inputs to and capabilities of a MEP coordination tool, and providing input for MEP test case of a 4D planning tool developed in CIFE.

Swinerton & Walberg has allowed the researchers to attend MEP coordination meetings for the McCullough Annex Building at Stanford. This access to the project, combined with the major challenges for MEP coordination on the project, resulted in excellent data concerning the information required, process of coordination, typical problems, and methods of resolution. The researchers also conducted interviews at Rudolph & Sletten, Swinerton & Walberg, and Therma to learn about MEP coordination processes in these firms.

Information from the coordination meetings and interviews provided the main basis for the a description of MEP coordination prepared by the researchers. Based on this understanding of practices for MEP coordination, the researchers listed inputs to a possible tool to assist with this process and identified possible capabilities of this tool.

Findings regarding MEP coordination practices

One of the findings to date is the description of current practices for MEP coordination, along with problems and opportunities to improve. We described these findings in the

meeting and the advisory group offered the following comments:
The trend is for less detail in the MEP drawings produced by the engineer. The level of detail for engineering drawings is directly proportional to the cost per square foot of the facility.

Coordination requirements are not substantially diminished when the engineer prepares a 3D model and drawings based on it because the specific components and their detailed configuration are not known at that time. This information is required detail the routing of piping and duct. It is available only when the contractor details the system and buys or fabricates the components.

Better informing owners regarding the need for building space for systems and the scope and duration of the MEP coordination process is a major opportunity to improve. On complex projects with likely changes in the design of MEP systems, budgets should include contingency for the cost of these changes.

Findings regarding sequential comparison process

The sequential comparison process was discussed in detail to refine the current description and identify variations. The architects, consulting engineers and specialty contractors agreed that researchers' summaries accurately describe the current coordination process. Most agreed that this process is followed during both the design stage and the coordination stage of a project. Exceptions and variations to the process are noted below.

When an interference is discovered during coordination, the decision to move a particular component is usually based on cost. This analysis and comparison of cost to move includes three aspects: material cost, engineering cost to redesign (if required), and installation cost. The relative size of the two components is also considered. Both size and cost determine which component will move to resolve an interference.

There were many comments and alternatives offered regarding interferences between HVAC dry ductwork and graded piping. The size of the HVAC ductwork prevents relocation when space is critical. However, the slope of a graded drain line is a major constraint. Possible solutions include dividing the duct and rejoining joined beyond the graded line. Another solution is to route the pipe directly through the HVAC duct as long as proper sealing is provided. An additional alternative is to route the graded drain line around the HVAC Dry duct. This solution is only used when the slope of the graded line was already more than required. Lastly, an additional riser can be added to drop the line to the next floor if none of the above alternatives will work.

Other components and systems that are considered in the sequential comparison process are pneumatic tubing which consistently causes problems, and fiber-optic cables which require large radius bends. Although both of these fall under the category of controls systems, they must be taken into account earlier in the coordination process. During the discussion, it was also mentioned that fire protection main lines did not need to be graded unless the system was a dry type. In addition, the description should highlight priority for large cable trays and bus ducts in the comparison process. These components require a higher priority due to their large size and multiple runs, which are usually routed together.

Software for MEP design and coordination

Discussion of software for design and coordination of MEP systems during the meeting included the following points:

- Engineers have specified that all trade contractors must use AutoCAD to prepare drawings.
- Trade contractors use different systems that support their needs for fabrication and installation.
- Control of simultaneous changes is a major problem for use of a shared CAD model.
- The group suggested adding the following programs to the software that the researchers listed on Attachment 6: Visio, Intergraph Microstation.
- The group identified the following problems with the use of a 3D model by the engineer to design and coordinate MEP systems: inability to include exact configuration until detailing and procurement, need to assume an appropriate level of detail for the model without input from its user, and inability to change quickly.

Plans for MEP coordination tool

The advisory group discussed inputs to the prototype tool for MEP coordination to define the scope of design included and made the following comments:

- add supplemental overhead structures, such as for support of overhead doors because these members frequently cause coordination problems
- provide further detail for instrumentation and control, including limitations on bending radius for fiber optic cable and bundles of pneumatic tubing

The discussion next focused on capabilities and outputs from a MEP coordination tool with the following comments:

- include a check against design standards and vendor requirements, such as straight pipe lengths up and downstream of flowmeters
- include checks for supports and restraints
- include “halo” spaces for access to install and maintain
- anticipate information exchange over the internet
- consider the capability to call for a coordination check at any time during the preparation of shop or coordination drawings; a complete system would then give advice concerning routing priorities, construction, and operation and maintenance
- a complete system would include capability to produce fabrication drawings for duct or pipe, or a possible link with other software that provided this capability

Third meeting of the Industry Advisory Group (6/4/98)

The objectives for this third meeting of the Industry Advisory Group for MEP coordination were to report progress, describe plans for future activities, and obtain comments and input from the advisory group concerning the knowledge for MEP coordination, the prototype MEP coordination tool, and plans for the research during the 1998-99 academic year. 11 members attended.

Research activities since second meeting

The researchers focused on three activities since the second meeting of the industry advisory group: collecting knowledge concerning MEP coordination by attending project meetings and conducting interviews, developing a prototype coordination tool, and obtaining funding for phase two of this research. I attended MEP coordination meetings on three projects: McCullough Annex at Stanford, Applied Materials Technology Center, and CCSR at Stanford. He also conducted interviews concerning processes for MEP coordination with Hathaway Dinwidde, Swinerton Technologies, and Building Operations Support Corporation.

Developing the prototype coordination tool, as further described below, involved selecting knowledge to include and building an application of Power Model Software that identifies physical interferences and instances of noncompliance with design criteria.

The researchers also submitted a successful proposal to Stanford's Center for Integrated Facility Engineering to support work on the project through August 1999. This continuing effort will focus on collecting and adding knowledge related to construction and facility operations to the coordination tool, increasing its functionality, and testing it on projects.

Process and scope for MEP coordination

The flow chart titled "Current Practice with Light Table" and included in the attached handout for the meeting describes the researchers' understanding of MEP coordination on many projects. The meeting attendees offered the following very helpful comments concerning the scope and process of MEP coordination:

- Several predictable types of areas are congested with MEP systems on many projects and therefore merit coordination activities. These include entry points for building services, equipment rooms, building cores, equipment pads in the yard, and underground utilities and services. It is very important to identify these and other parts of buildings that merit MEP coordination prior to construction to define the most effective scope for coordination on each project. Field coordination of MEP systems may be adequate for less congested areas.
- Building volumes available for MEP systems (such as between corridor walls below beams and above suspended ceilings or below raised floors) along with the configuration of the building structure set the boundaries for MEP coordination. Defining these volumes is an essential starting point.
- Assigning zones for MEP systems prior to the contractors' preparation of coordination drawings is beneficial for some types of projects, but not all. Complex facilities may require so many exceptions that this step is not beneficial.
- Biotech projects and medical facilities under OSHPOD jurisdiction typically present major challenges for MEP coordination.
- Obtaining input regarding operations and maintenance of the facility at the earliest possible time is an essential part of MEP coordination.

Knowledge for MEP coordination

The researchers reviewed their current understanding of the knowledge required for MEP coordination. We have collected extensive knowledge concerning design criteria, along with a few examples concerning construction, operations, and maintenance. The slides concerning knowledge in the handout for the meeting and the table titled "Coordination Inputs & Issues" give examples for each type of knowledge. These examples include the following systems: signal, electrical, plumbing, process piping, mechanical, and fire protection. Most of our current knowledge of criteria for decisions in MEP coordination has come from coordination meetings because specific situations and problems are the most effective way to bring out the knowledge.

The meeting attendees also suggested acquiring further knowledge from architects regarding consideration of MEP systems in building conceptual design and from construction crafts regarding detailing, fabrication, and installation. The suggestions for architecture firms were CAS, Dowler-Gruman, Erlich Rominger, Flad, and WHL. Specialty contractors that involve construction crafts in detailing include CMI, Cupertino Electric, and Therma.

The meeting attendees identified the following additional types of important knowledge: code requirements regarding separation and minimum clearance, limitations of materials of construction (e.g., inability to make a two inch offset), and design requirements to support all stages of the facility lifecycle, including operation, maintenance, replacement, retrofit, and decommissioning.

Prototype MEP coordination tool

The researchers have developed a prototype tool to assist with MEP coordination and described the revised work process necessary for its use. As in the current process, it begins with preparation of separate coordination drawings by each trade contractor.

Combining these separate coordination into a 3D model of the facility, the next step, is a major addition to the work process. The meeting attendees indicated that AutoCAD files should be available from most specialty contractors. The feasibility of obtaining this input would increase if the coordination tool could accept 2D drawings and add elevations for input to the 3D model.

The next step in the revised process is analysis of the 3D composite CAD model by the MEP coordination tool. The analysis by the prototype tool involves identifying physical interferences and variations from design requirements. The next step in the revised process is resolving the interferences using advice from the tool. The contractors then prepare coordinated shop drawings for approval, fabrication, and installation.

Thomas Korman demonstrated operation of the prototype tool for MEP coordination. This included entry of component data, examples of the hierarchy and attributes for objects in the MEP systems, cross section and plan views, and analysis by system and area. The analysis involved relocating objects and identifying the resulting physical and functional interferences. It worked.

The current version of the prototype tool has several limitations that further development will resolve. These include the requirement to input each object and limit its shape to a rectangular solid (will resolve by an interface with AutoCAD); use of a workstation platform (complete or compiled versions will run in a Windows environment), and relatively slow run time (further programming will improve efficiency). The attendees provided very positive feedback concerning the performance of the prototype tool and agreed that overcoming these limitations is feasible.

The attendees offered the following very helpful comments and suggestions to increase the capability and potential use of the prototype tool for MEP coordination:

- Clearly define the total volume available for routing MEP systems, including ceiling planes and all walls. Make sure that the MEP coordination tool checks fit within this envelope defined by the structural and architectural design in addition to analyzing for spatial and functional compatibility between the MEP systems.
- Establish conventions for CAD files from specialty contractors. These include: total volume available for MEP systems, areas of the building or plant to coordinate, level of detail for each type of system, and 0, 0, 0 reference point for all trades to use. View the composite model of MEP systems for analysis by the tool as layers added to the architectural and structural design.
- Revise the entry of component data to follow as closely as possible the current practice for definition of systems and data entry in each of the trades. For example, dimension supplemental steel from column lines and use invert elevation and diameter to define piping.
- Emphasize problem identification over recommendations for solution. For problems identified, fully define the location and type of problem, including source of the violated criterion. Continue to rely primarily on the experience and creativity of the engineers and specialty contractors involved in MEP coordination for alternatives and solutions.
- For effective use in MEP coordination, the tool or its interfaces must allow full

visualization of the systems, including sections cut at any point and direction. Make sure the 3D composite CAD model also includes the capability to specifically locate interferences and to separate the coordinated design of each trade's work. Do not rely fully on color to distinguish systems; expect that parts of the output from MEP coordination will be printed out and faxed to the jobsite.

- Provide additional flexibility for the use of "halos" to reserve space around system components for installation, operation, and maintenance. This should include limiting to one side or surface of a component, variable size halos on different sides, and maintaining a specified buffer zone or separation between components.
- Recognize the changes in priorities for individual systems within different facilities and even in different areas of the same facility. Include the capability to define different design criteria, such as the required slope of lines, on different projects.
- Provide space for racks and large supports.

General discussion and actions

If the specialty contractors are involved early in the project, they should provide input to the schematic design regarding floor layout and space requirements. For the most effective overall approach to MEP systems, it is very important that detailing, fabrication, and installation receive a balanced consideration during the early design stages. For example, the "land grab" during conceptual design should carefully consider the location, size, and shape of electrical and mechanical equipment rooms and space for distribution systems to minimize the scope and cost of MEP systems. Early construction input to schematic design greatly increases the visibility of cost.

The group felt that the need for 3D designs by specialty contractors would not be a major restraint to using the coordination tool, however it would limit the number of firms that could be involved. Some projects now use a FTP site to transmit AutoCAD files. A reliable interface with AutoCAD for input and output of the MEP coordination tool should allow the necessary data exchange. The researchers will discuss this with AutoDesk.

The group suggested the specific actions listed above in continued knowledge acquisition and development of the tool. If possible, we will add a programmer to expedite addition of the new capabilities. Several members offered access to projects and staff experienced in MEP coordination to obtain further knowledge and test future versions of the tool.

Fourth meeting of the Industry Advisory Group (6/9/99)

The objectives for the fourth meeting of the Industry Advisory Group for MEP coordination were to report progress, demonstrate the tool for MEP coordination, and obtain feedback on progress and plans for future research activities. 7 members attended.

Research activities since last meeting

The major activities on the research project since the last meeting were acquiring and analyzing knowledge, developing a knowledge structure, identifying objects to include for each system in the tool, developing a new version of the tool, and writing a link to AutoCAD.

The structure for the knowledge in the MEP tool includes knowledge concerning design intent, construction, operations, and maintenance. Each of these knowledge domains includes two categories: knowledge about a specific component without regard to any other component and knowledge about a component in relation to other components. The knowledge is represented in the tool by specific values of slots that are a part of frames.

The researchers also identified objects for each system included in the MEP coordination tool. This defines the scope and level of detail for the tool.

With the assistance of Jai Shi, a Computer Science undergraduate at Stanford, the researchers built a Java version of the tool. It includes the ability to import geometric data from an AutoCAD file and analyze the systems against rules based on the design, construction, and operations knowledge.

MEP coordination tool, Version D

I demonstrated the latest version of the tool for MEP coordination. This included importing an AutoCAD file with several systems routed in a corridor and analyzing the configuration to identify the four types of interferences defined by the knowledge in the model: hard, soft, functional, and forward/future. The demonstration included identifying physical interferences and coordination problems and relocating the objects to resolve the problems.

During the demonstration, the attendees offered the following very helpful comments and suggestions regarding specific capabilities of the tool for MEP coordination:

- The tool will need to include all branch lines and the capability to modify these lines as required by relocation of the main line to resolve a coordination problem.
- Add hangers to the list of objects for each system.
- To make the tool easier to use, modify the component property box or replace it with a toolbar to display only the essential information needed during analysis.

General discussion and actions

The group made the following general comments and suggestions concerning the tool:

- Design the tool to apply as early as possible in a project. Consider using it to assist in selecting the most beneficial level of MEP design scope and system definition.
- Consider adding a capability for the tool to capture and communicate overall guidelines for system coordination, such as those typically established at the first coordination meeting for a project.
- Use the tool to implement decisions regarding space allocation to each design discipline and construction trade.
- The design of the tool needs to recognize that effective MEP coordination processes are collaborative and involve reciprocal concessions.
- The level of detail for the objects should vary inversely with space available for MEP; focus on priority rules to keep the system simple and increase potential for use.
- Users of the system will want full visibility of changes made during coordination and their implications; otherwise they will resist use.
- Provide the capability to add special systems needed on a specific project.
- Investigate applicable codes as sources of requirements for the system designs. Also consider possible use of the coordination tool as a means to clarify responsibility for code compliance in each system.
- Make sure the system has the capability to export the coordinated design in a form that will allow the specialty contractors to complete their material takeoffs and spool sheets for fabrication. Ultimately, it will be most useful if available on a PDA for use by foremen to solve problems in the field.
- Field coordination, including installation sequence, depends fully on site conditions. It is therefore best left to coordination meetings at the jobsite.
- Designing the system to operate with input from “elevated” 2D drawings rather than 3D drawings would greatly increase the rate of acceptance and use.
- On current projects it is very difficult to obtain 3D design from the architect and the structural engineer.
- Obtain input from a facility operations group, such as Stanford’s.

The group discussed the best point in the project to use the tool for MEP coordination and agreed on the earliest time when the location and routing of components is defined. For certain complex projects, schematic design is not useful because coordination requires configuration. Highly congested areas may require two levels of analysis: global to define volumes for each system on each floor and detailed to complete the coordination. Solving difficult problems often requires multiple plan and section views of the systems.

The group identified measures of good coordination: maximum possible use of prefabrication and how well the system goes in as indicated by the number of modifications to fabricated components.

Appendix C – Data Collection Sources

Project site visits	Contractor
Applied Materials Tech Center (Arques Campus) – Sunnyvale, CA	Hathaway/Dinwidde
Elihu Harris State Office Building – Oakland, CA	Hathaway/Dinwidde
Metreon Sony Entertainment Center – San Francisco, CA	Hathaway/Dinwidde
Cantor Arts Center, Stanford University - Stanford, CA	Rudolph & Sletten
Intel Ronler Acres - Portland, OR	Rudolph & Sletten
Visa III Project site visit - Foster City, CA	Rudolph & Sletten
Electrical Engineering Bldg. SEQ Project – Stanford, CA	Swinerton & Walberg
GAP Bldg. restoration project – San Francisco, CA	Swinerton & Walberg
McCullough Bldg., SEQ Project – Stanford, CA	Swinerton & Walberg
Chiron Project – Emeryville, CA	Therma Crop.
Santa Clara Valley Medical Center – Santa Clara, CA	Turner Construction

Personal Interviews	Contractor
Alfred J. Sanchez Inc., Independent Consultant	Alfred J. Sanchez Inc.
John Pianca, Vice President	Building Operations Support Corporation
Craig Howard	Design Power
Mark Belgarde, Mechanical Design Consultant	Flack & Kurtz, LLP
Todd See, Mechanical Design Consultant	Flack & Kurtz, LLP
Rick Lasser, MEP coordinator	Hathaway/Dinwidde
Mat Hayashi, Project Manager	Kinetics
Daryl Phillips, MEP coordinator	Linbeck
Mike Piotrkowski, MEP coordinator	Rudolph & Sletten
Vic Castello, Electical Contractor President	SASCO Valley Electric
Mike Rowe and Logman Ma	Scott Mechanical
Galen Hobart, Project Engineer	Superior Automatic Sprinkler Company
Galen Hobart, Fire Protection Designer & Detailer	Superior Fire Protection
Greg Parrett, Specialty Contractor President	Swinerton Technologies
John Mack, Mechanical & Piping CAD Manager	Therma Corporation

Project Studied
CCSR Bldg. – Stanford, CA
McCullough Annex Bldg, SEQ Project – Stanford, CA
Sequus Pharmaceuticals Pilot Plant - Menlo Park, CA

Trade Shows
ASHRAE Winter 1998 Meeting and Exposition - San Francisco, CA
Pipe Trades Training Center Expo ‘98 -San Jose, CA
ASHRAE Winter 2001 Meeting and Exposition – Atlanta, GA

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