CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

MEP Coordination in Building and Industrial Projects

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CIFE Working Paper #54
March, 1999

STANFORD UNIVERSITY

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Abstract

Coordination of mechanical and electrical systems to detail their configuration provides a major challenge for complex building and industrial projects. Specialized consultants and contractors design and construct these systems. Computer tools can assist with this activity, but fragmentation of responsibility for these systems and the knowledge required for their design make this difficult. This paper reports initial results from a research project to develop a computer tool to assist in coordinating MEP systems. It describes current practice, a revised work process using a computer tool, the required knowledge, development of a prototype system. These results confirm the feasibility of capturing specific types of distributed knowledge required and developing a computer tool to assist with MEP coordination, along with the potential to implement the tool and significantly improve this important project process. Phase two of the project, now underway, will add construction and operations and maintenance knowledge to the tool and further develop its capability.

Chapter 1: Research Need, Objectives, and Method

1.1 Challenge and Need

This paper describes initial results from a research project at Stanford's Center for Integrated Facility Engineering. The purpose of this research is to increase the performance of project teams and facility managers in meeting objectives for complex buildings and industrial facilities through improved integration and mechanical, electrical, and plumbing (MEP) coordination. The method for this research first involves collecting knowledge applied by engineers and detailers during MEP coordination. This knowledge is very specialized; therefore, is very difficult for one discipline to know the requirements of the other trades. The researchers are representing this knowledge in a computer tool that can identify several types of problems in MEP coordination and make recommendations for solutions satisfying the multiple types of constraints.

MEP coordination presents an unusual challenge for practice and research. Advanced plant design systems can provide models to assist in coordination, but they are generally not used on hospitals, laboratories, semiconductor wafer fabs, or biotech manufacturing plants. Detailed design and construction for these complex facilities are fragmented because specialty design consultants and contractors perform this work. The root cause of the MEP coordination problem is not the lack of technology but the need to apply available technology tailoring to a specific set of business and technical conditions. Object-oriented 3D models could allow a revised process of coordination. However, capturing the distributed knowledge concerning the different types of systems and tailoring the software to meet the special needs of MEP coordination remain major challenges. Success with this activity would support major improvements in design, coordination, construction, commissioning, operation, maintenance, and retrofit for new uses.

The specifications assign responsibility for coordination to the specialty or trade contractors, including checking for clearances, field conditions, and architectural conditions. The process of MEP coordination involves locating components and branches from all systems in compliance with design, construction, and operations criteria. The current process of sequentially comparing 1/4 inch/foot scale transparent drawings for each system over a light table adds significant cost to many projects and can add significant duration.

Improving the coordination process for mechanical, electrical, and plumbing (MEP) systems on complex buildings and light industrial projects presents a major opportunity to improve project performance through increased integration. Coordination involves defining locations for branch components of systems in congested spaces to avoid interferences and comply with diverse design and operations criteria.

Several problems in current practice create the need to improve. Limited building space for MEP systems makes efficient design and construction much more difficult. On many plans and specs projects, accelerated schedules and decreased designers' fees do not allow detailing MEP systems by design consultants. The scope of work for specialty contractors on these projects increasingly includes "design assist" to complete the design for fabrication and installation. Design-build contracting, with different specialty contractors responsible for different systems, decentralizes design responsibility and increases the potential problems and the need for effective coordination between the different types of systems. Fast track projects increase the challenge.

MEP systems must satisfy multiple objectives and criteria for design, installation, commissioning, operation, and maintenance. Different types of specialty contractors (e.g., process piping, HVAC piping, HVAC ductwork, plumbing, electrical, fire protection, controls) are responsible for these systems. Example of diverse criteria for system design include spatial (avoiding interferences), functional within a system (flow or gravity drainage), adjacency or segregation, system installation (layout dimensions, space and access for installation productivity), and testing (ability to isolate). On complex buildings and plants, expertise and designs are required from diverse specialists -- essential fragmentation requiring horizontal integration between these different functions working in the same project phase.

The current work process is for design consultants or design-build contractors to design their systems independently. Coordination responsibility is then assigned to one firm, often the general contractor, the HVAC contractor, or a coordination consultant. The resulting process is slow and expensive. One general contractor estimated coordination costs as six percent of the MEP cost or two percent of the total cost on a light industrial project. An electrical contractor said that coordination cost equals design cost on projects in Silicon Valley; each are about three percent of the total cost for electrical systems.

At the low-tech end of the practice spectrum for MEP coordination, drawing plan views on transparent media and using a light table to overlay routing proposed by several contractors is easy to understand and change. However, this process often involves frequent and difficult meetings. Difficulty in visualizing complex systems in congested spaces often requires drawing multiple section views to accompany the plans prepared for initial routing. It is also very difficult to accommodate design change after coordination decisions.

At the other end of the spectrum, 3D CAD and other information technology offers the potential to improve this process and its results. Plant models provide major benefits for large hydrocarbon and power projects on which the Architect/Engineer completes the entire design. However, design consultants and specialty contractors prefer systems tailored to specific information needs for detailing, estimating, fabricating, and tracking their type of work. Current use of multiple systems (e.g., Intellicad, Quick Pen, Colorado) tailored to the needs of specific disciplines and trades limits overall effectiveness. The systems are not compatible and DXF transfer usually loses about ten percent of the database contents.

Complex configurations of MEP systems in congested spaces are very difficult to visualize. The less complete definition of systems in the "design assist" approach makes it very difficult to define scope of work for fixed price contracts. This increases the potential need for contract changes based on the increased cost of installing the system configuration that results from the coordination process. Also, the first contractor working in an area often optimizes routing for their systems, requiring expensive rework if this is not compatible with other systems.

As a result of these problems with current processes, the product of MEP coordination does not fully satisfy the objectives of any of the project participants. To improve project performance, the construction segments focused on complex buildings and high tech plants need increased horizontal integration between design consultants or design-build contractors to improve the effectiveness of the coordination process and better meet project objectives.

This first requires a simplified method to consolidate the designs from multiple sources to visualize and easily change the configuration for initial coordination. The next key need is to capture the knowledge required for application of diverse criteria in making coordination decisions. This will eventually allow partial automation of MEP systems coordination. For improved lifecycle performance of the facility, a major need is to increase vertical integration by reciprocal information exchange with facility managers and operators for the building or plant. Phase one of this research supports CIFE's integration goals by applying information technology to improve horizontal integration in the MEP coordination process, a major need on complex buildings and industrial projects. Phase two is addressing vertical integration with construction and facility management, two more major opportunities.

1.2 Research purpose and objectives

The overall purpose of this research is to increase the performance of project teams and facility managers in meeting objectives for complex buildings and industrial facilities through improved integration and MEP coordination. The folllowing objectives structure this project:

- shorten the duration and lower the cost of designing, coordinating, and installing MEP systems by reducing the number of meetings required and persons involved
- analyze project needs, information requirements and current process to coordinate MEP systems, along with needed improvements
- develop and implement a knowledge base concerning design, construction, and the facility lifecycle for use in analysis and advice during MEP coordination
- develop and test a tool to coordinate design input from each MEP discipline and trade on a complex building or plant project.

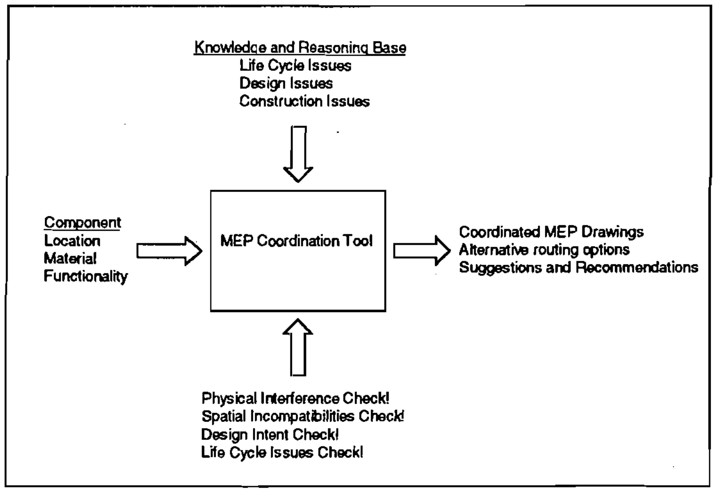
1.3 Research method and scope

This research seeks to capture knowledge of many engineers and detailers who are involved in the MEP coordination process. This knowledge is very specialized; therefore, it is very difficult for one discipline to know the requirements of the other trades. MEP coordination is a multi-discipline activity, which must consider each discipline and their knowledge of space requirements, installation practices, and maintenance needs.

The method for this research first involved participating in and collecting data regarding current coordination activities on complex buildings and industrial projects and analyzing these data to describe current coordination processes and identify potential improvements through the use of information technology for horizontal integration.

Based on this understanding of current practice, we then built a hierarchy of priorities for coordination to include geometry (physical interferences), functionality (meeting complex design criteria and design intent), construction (sequences, methods, access), and the remainder of the lifecycle (maintenance, repair, retrofit, replacement). The next activity was to represent this knowledge in a tool that, as shown in Figure 1, can make recommendations regarding functionality of the systems, construction plans and methods, and facility operations and maintenance.

Figure 1. Functionality of MEP Coordination Tool



The tool will allow users to integrate design of systems from multiple MEP specialty contractors into a common CAD model. This model of coordinated design will graphically depict the physical layout of all components and also contain attributes of the objects in the system.

1.4 Research activities

1. Define the scope and functionality for MEP coordination tool

To define the required functionality of the system, we described improved work process that the MEP coordination tool will allow. We expect that the tool will include capability for the following types of analysis and checking in support of the MEP coordination process:

- compliance with priorities for system location in MEP coordination, such as which system is routed "high and tight" for first installation and easier support
- avoidance of physical interferences between MEP systems and with structural or architectural features
- compliance with design requirements for system functionality, such as slope for

drainage, separation of water and electrical systems, such as less than 360 total degrees of bends in conduit to allow cable pulling

- reserving "halos" or access paths for construction, operation, or maintenance.

2. Collect and represent knowledge

Phase one of this research focused on the geometric aspects of MEP coordination. We also began acquiring knowledge concerning design constraints, construction of the system, and the remainder of the facility lifecycle. We continued this activity during phase two to gain the knowledge needed to implement this functionality related to vertical integration in phase two, focusing on object attributes. Planning for knowledge acquisition included preparing examples of attributes for key objects to use as a basis for feedback by interviewees, and identifying projects and experts.

We used several techniques and sources to acquire the knowledge needed for the MEP coordination tool. We completed additional case studies of MEP coordination on projects. We further reviewed engineering literature and vendor data to identify and describe design constraints and component attributes. We also interviewed engineers, general contractors, specialty contractors, and, operators to obtain knowledge about attributes for specific objects.

3. Build the MEP coordination tool

Building the system involved expanding the object hierarchy and slot tables developed in the Power Model software for the horizontal integration tool in phase one. We then programed methods and rules to perform the analysis of preliminary designs and provide feedback in the MEP coordination tool. We also added links to CAD software for input and output, seeking compatibility with AutoCad, Bentley, and software used by specialty contractors, such as Quick Pen for mechanical work.

4. Test and validate the MEP integration tool

Following programming and initial testing to assure that the tool includes the desired functionality, we will validate the system on a project by comparing the coordinated design obtained by following advice from the system with the actual design developed by the project team. The researchers will select a representative portion of a project that presents challenges for MEP coordination and develop the design following advice from the MEP integration tool. We will then compare the detailed configuration with that actually developed for the project, identify the differences, and discuss them with the project team. If these differences indicate a need to acquire and represent additional knowledge in the tool, we will complete this and further validate the system. Based on the results of initial testing and input from the IAG, we will identify additional knowledge, further programming, and further testing needed to complete the MEP coordination tool. We will then take these actions to complete the agreed scope and capabilities of the tool for phase two.

5. Hold meetings of industry advisory group (IAG)

Phase one of this project benefited greatly from a committed and active IAG. Each of the types of firms involved in MEP coordination is well represented. At IAG meetings during Phase 2, we described the MEP coordination tool, give the results of testing and validation, and summarize our current plans for refinement. We will obtain comments from the IAG regarding each of these topics and suggestions for actions to refine and further test the tool. The final meeting of our IAG will focus on overall results of the project, including comments on results of testing and validation, conclusions, recommendations, and plans for future research. We also expect our IAG to assess the potential for a sponsored project to further develop the integration tool and, hopefully, form the core group to make it happen.

6. prepare CIFE report, journal papers, addition to web page

We will summarize the results of developing and testing the MEP coordination tool and conclusions concerning increased understanding of MEP coordination and recommendations for practice. We will also highlight interesting research issues for future MEP projects and actions to support commercialization of the tool. We will disseminate results of this research by a CIFE report, journal papers, and a web page. The CIFE report will describe the research activities and results and will a description the MEP coordination tool. We anticipate two technical papers, one with a research focus and one for practice. We will also post the results of phase one and plans for phase two on the web page created for this project.

1.5 Readers' guide for this report

Chapter two of this paper describes the current process for MEP coordination, including differences on projects using different delivery approaches. Chapters three and four define the capabilities and knowledge required for the MEP coordination tool and the revised work process to use it. Chapter five describes our process to develop and test the tool. Chapter six highlights our preliminary conclusions and recommendations regarding the use of a tool to improve MEP coordination.

Chapter 2: Current practice for MEP Coordination

Understanding current practice for MEP coordination is essential to recognize the opportunity to improve and to develop effective computer tools that support improved processes. Recognizing fundamental constraints from industry organization is essential to develop a tool with potential for implementation. The following description is based on interviews with 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. This section ends with a summary of the limited published background concerning MEP coordination and related research.

2.1 Overview of Current Practice

Complex buildings and light industrial projects, using either the design-bid-build approach, the design-assist approach or the design-build approach, require coordination for MEP systems. The engineer first prepares mechanical, plumbing and electrical specifications, assigning full responsibility for coordination to the specialty contractors, including checking for clearances, field conditions, and architectural conditions. On design-bid-build projects, the engineer also prepares diagrammatic drawings of MEP systems to establish the scope, materials, and quality, but not detailed layout or installation instructions. The specification requirements and drawings provide the information inputs for MEP coordination.

After contract award, the process for MEP coordination begins with the specialty contractors (primarily HVAC wet and dry, plumbing, electrical, and fire protection) preparing shop drawings, generally with a scale of 2.1 centimeters per meter (1/4 inch per foot), to route systems, detail for fabrication, and locate for installation. Representatives from each of the specialty contractors then sequentially compare their shop drawings using a light table. They also prepare section views for highly congested areas, identify interferences, decide which contractor will revise their design, and submit requests for information regarding problems that require engineering resolution. This sequential comparison overlay process follows a consistent priority described below and continues until all interferences are resolved. The product of this process is a set of coordinated shop drawings that are submitted to the engineer for approval. The specialty contractor may also submit the cost impacts of coordination, which can be significant if the coordinated system differs greatly from typical configurations.

The current process for MEP coordination presents the following problems on many projects:

- The scope of services by the engineer does not include coordination; detailing information defining configuration is required and only available from the specialty contractor.
- Responsibility for engineering, design, detailing, and as-builting is difficult to define,
- The scope of coordination and the responsibility for each trade are not clearly defined.

- The coordination process is slow; it can become critical path for systems installation.
- The current approach requires extensive commitment of key staff having very valuable experience by the engineer, general contractor, and specialty contractor.
- Constructible design depends on the construction knowledge of contractor's detailer.
- Operable systems depend on the operations knowledge of contractor's detailer.
- The process creates potential for commercial disputes concerning scope and complexity; allowance for scope growth during coordination can increase the cost of MEP systems and the construction schedule of projects.

The following sections describe the process for MEP coordination in greater detail. This description begins by identifying the differences in requirements and processes for this activity under different contracting approaches on projects.

2.2 Overview of the project delivery process

This section gives a general overview of the process that a typical specialty contractor takes in order to procure, design, and build work. The process is initiated by the owner's decision to construct a facility and ends with the final product being turned over to the owner upon completion of the project. The process includes the following phases: conceptual design, bidding, award of contract, start of project, engineering, submittal and approval, pre-construction and fabrication, and installation. Each of these phases will be described in more detail in the following sections.

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 usually results with a set of schematic design drawings, which exemplify how the owner envisions the building concept. During the initial phase of the conceptual design layout sketches with notations about how the spaces are to be used, approximate square footage, ceiling heights, etc. are created. In this stage of the decision making process, the owner determines what the general use of building will be, and, depending on the owner's needs, the building's function is determined. The function of the building may range from office space, laboratory space, housing, hospital space, to industrial manufacturing space. Once the function has been determined, an architect is selected, and the building is schematically designed in response to the owner's needs.

The final set of schematic design drawings consists of a building layout plan, which includes elevations, wall layouts, general floor plans, etc. Once the schematic design has been developed with the general function of the building in mind. The building layout plan is turned over to an engineering design consultant to design and preliminarily route the various building systems. An owner's need date is then set, and a general schedule is developed to accomplish construction in that time frame.

2.2.2 Bidding and contract award

In both the traditional design-bid-build scenario and the design-build scenario, bid packages are distributed to pre-qualified specialty contractors for bidding purposes. The bidding stage is usually the point where the specialty contractor's interaction begins in the project development process. A typical bid package for a design-bid-build contract scenario consists of the architect's schematic design drawings and engineering design consultant's plans. A typical bid package for a design-build contract scenario consists of the architect's schematic design drawings and the engineers basis-of-design, which consists of user specifications and requirements.

During this period, the specialty contractor estimators review the drawings and specifications. A construction estimate concerning the total cost to build their particular segment of the project (HVAC, Electrical, fire protection, etc.) is prepared. The estimators first begin by preparing preliminary layout plans based on the drawings and specifications or BOD. The preliminary layout usually consist of lines drawn on the architectural floor layout plan indicating the route the system will eventually take. This done for purposes of determining the linear footage of a particular system, number of connection points, number of turns, etc. The estimator then prices out the material, engineering labor, fabrication cost, and field labor, permit fees, and taxes. This total cost is then reduced to a per linear feet cost. In most specialty contractor organizations, a review of the estimator's bid is conducted with the management team for additional input about labor, fabrication, material, etc.

In preparing estimates most specialty contractors use historical project data to obtain ballpark figures. For a detailed estimate to be completed, a contractor must have a detailed design. The estimates are rough in nature, which include material, labor, and major equipment. Often high margins are built into the estimates to account for unexpected contingencies, which are not disclosed, to the owner.

Once this process is completed, the estimator drafts a proposal for the customer, which includes any clarification of inclusions and exclusions. The bid proposal is then reviewed by the general contractor, architect, and owner to determine the lowest, most responsible bidder for the project.

The general contractor awards the bid to the lowest responsible specialty contractor and prepares a contract for signing by the successful contractor. After the specialty contractor has been awarded the contract, the specialty contractor makes preparations to build the work. These preparations include completing a detailed design, producing 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 bid material, which includes plans, estimates, preliminary design plans, etc. to the superintendent or foreman of project who will actually supervisor the construction. Within the specialty contractor organization, there is, typically, a pre-design meeting with the engineer, estimator, field foreman, and operations manager. A review of the schedule for needed dates is performed in addition to setting up project minutes, which is reviewed weekly for updates. A review of the estimator's design and layout is performed. Any additional improvements for the particular building system layout are considered, and possible cost savings actions are taken where they are found.

2.2.4 Engineering, submittal and approval

In both the design-bid-build and design-build project delivery methods, the design and layout is once again reviewed and confirmation is made with all local and governing jurisdictions. The design is reviewed for any possible errors, or changes. Coordination layout with other trades, including structural, is performed to make sure that the all the building systems will fit inside the building. (Additional information regarding engineering design process and the MEP coordination phase will follow in later sections.)

The detailed design drawings furnished by the specialty contractors are submitted for approval for construction. A review is typically performed by the architect, engineering design consultant, local city fire department, and the owner's insurance agency. Drawings are received back with comments. If drawings are not approved, then marked corrections are made and resubmitted for approval before a building permit is issued.

2.2.5 Pre-construction and fabrication

During the fabrication stage, a typical specialty contractor's engineering department lists all materials needed for fabrication. The fabrication manager then fabricates all necessary pipes, fittings, hangers, heads, valves, etc. and prepares them for shipment to the job site. It is the fabrication manager duty to also procure any major equipment that is necessary for construction such as, cooling towers, large pumps, air handlers, exhaust fans, etc. Engineers prepare installation packages (installation drawings, list sheets, copies of permit etc.) for the installation foreman. The entire job is then shipped to 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 job, complexity of job, and days needed to install before the project is to be turned over to owner.

Once the job foreman and crew receive shipment at the site, the materials are distributed to the general location inside the building for installation. Various components are then installed in accordance with the drawings. Upon completion, inspectors are called out for testing of the entire system. Any discrepancies are corrected before any permits are signed off by the building inspector. Architecture items are then finished off (ceiling, carpeting, painting), and the building is finalized by all jurisdictions for compliance. Once all items are in compliance, the owner is issued a building use permit and the owner is permitted to move in.

2.3 MEP building systems in building design process

This section is included to familiarize the reader with what is meant by the term MEP and how it is referred to in the construction industry. The remaining sections will deal with placing the MEP process in the context of both the traditional Design-Build and Design-Bid-Build project delivery methods.

2.3.1 Definition MEP building systems

MEP is an acronym that has been used historically to describe the mechanical, electrical, and plumbing systems in building and industrial projects. With increases in the functionality and complexity of systems, projects now include much more than just the traditional mechanical, electrical, and plumbing systems.

The scope of the MEP activity has been extended to include additional systems such as fire protection, controls, process piping, and telephone/datacom. Although these additional systems seem to fall under the historical categories of mechanical, electrical, and plumbing, they are most often installed by individual specialty contractors.

2.3.2 Design of MEP systems under design-bid-build contracts

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 are usually in the form of the space and shape of the structure as well as the aesthetic aspects of the building.

In the design-bid-build project delivery method, the architect employs an engineering design consultant to work under them for the purpose of designing the MEP systems. It is the engineering design consultant's responsibility to design each system in the building. These systems include HVAC dry, HVAC wet, plumbing (gravity driven systems), plumbing (pressure driven systems), electrical, and telephone/datacom. In more high-tech facilities, this list would also include process piping.

In designing the various systems, the engineering design consultant performs a detailed analysis and prepares design calculations for each of the systems. Sizing of each system component is made. This information is conveyed to the specialty contractors in the form what is referred to as contract drawings or design drawings. The are referred by their particular trade or discipline, i.e., mechanical design drawings, electrical design drawings, plumbing design drawings, etc. (The level of detail provided to the specialty contractor will be described in a following section.)

2.3.3 Design of MEP systems under design-build contracts

In the design-bid project delivery method, the architect still functions as the prime design consultant. The are responsible for how the space is utilized in the building which is a direct result of the owners needs and requirements. In a design-bid contract, the architect employs an engineering design consultant, just as in design-bid-build; however, the main difference between the two project delivery methods is the function that the engineering design consultant serves.

The engineering design consultant serves as an entity, which prepares specifications regarding the various MEP systems. These specifications are usually referred to the Basis of Design (BOD). The engineering design consultant makes recommendations regarding required air flow to a particular room, required power requirements, and necessary flow rates to various locations in the building, all in order to meet the owner's needs and requirements. It can be argued that the engineering design consultant is there to assist the architect in preparation of specifications only.

The engineering design consultant does not prepare any drawings for bidding purposes or for fabrication. Only preliminary calculations are made to determine service loads in particular rooms. Theses service loads are based on indications made by the user of the facility. No sizing of components or any attempt to route building systems is made.

The contract drawings include a layout of the building as determined by the architect and owner's needs. Specifications regarding the individual building systems are provided to the specialty contractors. These specifications may include particular requirements on equipment to be used in the facility or design criteria for specific building systems that must be met. The specifications are written from a design performance point of view, meaning that the final design must meet the design criteria set forth by the architect and engineering design consultant. The specifications in combination with the schematic design drawings are given to the specialty contractor for purposes of routing of the system and performing a detailed design.

2.4 General criteria that guide building system design

The purpose of this section is to give the reader an insight into the complexity of the individual MEP systems. This section will focus on the critical design criteria of MEP systems, which guide the design process of the various building systems. The building systems that will be addressed will be the HVAC system, fire protection system, electrical system, plumbing, process piping system, and the telephone/datacom system.

2.4.1 HVAC system

HVAC stands for heating, ventilating, and air conditioning; HVAC systems generally include the following basic components: (1) a heat-generating system, (2) a cooling system, (3) an air-handling system, (4) a control system for hand adjusting and/or automatic monitoring of the system operation. The HVAC system is meant to provide complete conditioning of the air, which also may include the filtering out of dust and odors, freshening with outdoor air, adjustment of the temperature, and adjustment of the relative humidity.

Some factors that must be taken into account for HVAC systems are space for equipment, noise and vibration, space for air duct systems, and the properties of the building enclosure. Proper space must be allotted for the HVAC equipment. HVAC equipment is generally very large and bulky. To be operationally feasible, the equipment must also be strategically located. The equipment must be accessible for maintenance and replacement purposes.

Noise and vibration are other factors that must be considered during the design stage; this is critical for cooling equipment and large fans. HVAC systems require large spaces for air duct networks. These must serve the building's interior spaces and link up with the operating equipment, and the air intake and exhaust must connect to outdoor air at appropriate locations.

For HVAC system designers, the design parameters are set forth by the architect and design consultant, depending on the building purpose and use. For requirements beyond the minimum set by the architect, the Sheet Metal and Air Conditioning Contractors Association (SMACNA) guidelines must also be met.

2.4.2 Fire protection system

The purpose of fire protection systems is to make the building fire resistant and to facilitate the speedy evacuation of occupants in the event of a fire.

For fire protection systems, the design parameters are set in accordance with NFPA-13 (National Fire Protection Association). These are the minimum requirements. Fire protection systems designers must also contact local jurisdiction officials, and the owner's insurance rating agency (Factory Mutual, Industrial Risk Insurer etc.) for requirements beyond the minimum standard required by NFPA and Uniform Building Code (UBC) as amended by that jurisdiction.

2.4.3 Electrical system

For electrical system designers, the design parameters are set in accordance with the National Electric Code (NEC). These are the minimum requirements that must be met. Electrical system designers must also adhere to NFPA 13, and the UBC for requirements beyond the minimum set forth by the NEC. The major categories of the electrical system are supply, distribution, and lighting.

2.4.4 Plumbing system

The plumbing system consists of three major categories - gravity drained waste systems, pressure driven systems, and pumped waste. Plumbing design must meet the Uniform Plumbing Code (UPC).

The gravity drain systems includes sloped lines which must have a natural grade line. In addition, the gravity drained systems require vent lines for the entire system, to allow for open channel flow in the drainage network. The pressure driven systems include hot and cold water supply lines the various locations in the building. Lastly, pumped waste systems include all waste lines that must be driven by pressure rather than by gravity. All pumped waste systems must run in double contained piping systems.

2.4.5 Process Piping system

Process piping systems generally include gas supply for laboratories, hospitals, and manufacturing facilities. These include oxygen, nitrogen, hydrogen, helium, argon, etc. The Toxic Gas Ordinance (TGO) and the Uniform Fire Code, Article 80 govern a majority of the process piping system.

2.4.6 Telephone/datacom system

In recent years, the telephone/datacom systems have become more complex and more important in buildings. The telephone/datacom system use fiber optic lines extend throughout the facility.

2.5 Need for MEP coordination

Architects generally focus on form, space, finishes, and other features that determine the appearance and use of the building. This section will describe what creates the need for the MEP coordination process in both the traditional Design-Build and Design-Bid-Build project delivery methods. As far as MEP coordination is concerned, the main difference between the different project delivery methods is the level of detail that is provided by the drawings.

2.5.1 Need for MEP coordination in design-bid-build contracts

The need for MEP coordination in the traditional design-bid-build scenario grows out of the nature of the how the contract is formed between the architect, design consultant, general contractor, and specialty contractors.

In the traditional design-bid-build scenario, the architect employs an engineering design consultant to design the major systems in the building. These systems include HVAC dry, HVAC wet, plumbing (gravity driven systems), plumbing (pressure driven systems), electrical, telephone/datacom, and process piping. The specialty contractors are not involved in the design of the various systems. They are simply considered installation and construction contractors to physically build the project.

The information to build and install the systems is conveyed to the specialty contractors in the form of contract design documents. These are what most specialty contractors refer to as the schematic design drawings. These drawings are not detailed enough to neither fabricate components nor construct the systems. The required size of components, such as conductor wire, duct dimensions, pipe diameter, are called out on the drawings, but no scaling of the components are shown in the drawings. A more detailed description of what is shown on the drawings is listed in the table below per MEP system.

Table 1. 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. Duct size is indicated on drawing, excluding insulation. Exact dimensions and location of major equipment are not shown.
Mechanical (HVAC Wet)	Drawings show major piping lines and number of connection points into VAV boxes. Size and material type are not indicated on the drawings.
Electrical	Outlet locations are shown on contract drawings. Some main electrical lines are shown. Electrical runs are not shown.

Plumbing	Plumbing lines are indicated by single lines on drawings. Pipe size is noted on the drawing. Offset from wall, insulation, and material are not indicated on drawing.
Process Piping	Rough location of outlet locations is shown. Piping lines are indicated by a single line on drawings and size is noted. Offset from walls, insulation, and material are not indicated.
Fire Protection	Fire protection plans indicate the preliminary layout of sprinkler heads. The specialty contractor must determine exact locations. Plans do not show loops or circuits.
Telephone/datacom	Only outlet locations are shown are drawings. Plans do not show loops or circuits.

It is the specialty contractor's responsibility to build the particular building system from these design documents. This requires the 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 includes joint type, member size, material type, connection mechanism, top elevation, bottom elevation, supply contents, and exact location references.

Table 2. 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. Duct sizes are indicated, with exception of insulation. Exact size and location of major equipment are shown.
Mechanical (HVAC Wet)	Drawings show major piping lines and number of connection points into VAV boxes. Size and material are indicated. All joints and connection points are shown.
Electrical	Outlet locations shown on contract drawings. Main electrical lines are shown. Exact location of circuit lines are not shown.
Plumbing	Plumbing lines are indicated by single lines on drawing. Pipe sizes are noted on drawing. Offsets from wall, insulation, and material are indicated on drawing. All joints and connection points are shown.
Process Piping	Outlet and drop locations are dimensioned. Piping lines are still indicated by single lines on drawing. Material and size are noted on drawing. Offsets from wall, insulation, and material are indicated on drawing.
Fire Protection	All sprinkler locations are dimensioned on reflected ceiling plans. All loops and circuits are shown on drawings. All joints and connection points are shown.
Telephone/datacom	All outlet locations are shown are drawings. Plans do not show loops or circuits.

The most common specification found in design-bid-build contracts states that it is the specialty contractor's responsibility to field coordinate the multiple building systems between the trades. Therefore, once the shop drawings have been produced, the coordination process begins. During this process all the specialty contractors meet to determine the exact location of each system. This process becomes very intense as each system location is compared with each other system to determine where interference's and conflicts occur. The exact nature of this process will be described in a later section.

2.5.2 Need for MEP coordination in design-build contracts

The need for coordination in the design-build contract directly stems from the contract set forth by the owner and architect. In the design-bid project delivery method, the architect functions as the prime design consultant. The architect employs an engineering design consultant whose function it is to prepare specifications regarding the multiple MEP systems. The specifications are based on performance characteristics that each individual system must meet. The engineering design consultant does not prepare conceptual drawings, nor do they prepare any design calculations.

The contract drawings, which are received by the specialty contractors, include only a layout of the building as determined by the architect. Using the design performance specifications and building layout drawings, the specialty contractor prepares a detailed design of the particular system. The contract requires that all systems be completely designed by the specialty contractors. The specialty contractor then becomes the engineer of record (EOR). This places all the design liability on the specialty contractor.

The specialty contractors are then responsible for the design, routing, and coordination of all the building systems. The engineering design consultants serve as reviewers of the final design who ensure that the design meets the specifications and owners requirements.

2.5.3 Contract requirements for MEP coordination

Most contract language indicates that the documents provided to the contractors only show the general arrangement of equipment and accessories located inside the building. The design consultant uses specific contract language, calling the specialty contractors attention work with the other trades to determine conditions of interferences that may affect the work. The contract language goes on further to indication that it is the specialty contractor's responsibility to accommodate the conditions. An example of this type of contract language is shown below:

> *The general contractor shall coordinate all equipment and accessories with all the trades and shall furnish any information necessary to permit the workable trades to be installed sense that door only bandwidth least possible interference or delay.*

2.6 MEP coordination process

This section gives an overview of the current process for MEP coordination and a detailed description of the sequential comparison of system designs that it includes.

2.6.1 Overview of process

Currently, the MEP coordination process begins when all building systems have been designed and preliminarily routed. The design is finished when all components are sized (e.g., conduits, pipe, HVAC duct), the engineering calculations completed, and the schematic drawings produced. This means that specific routing is not defined. Usually the HVAC and piping systems are sized during this initial design. Other trades such as electrical and fire protection are not, therefore some of the systems are drawn to scale while others are drawn simply as lines with references to component sizes.

The coordination process begins with the all the specialty contractors meeting together with all of their particular designs and preliminary drawings. The routing of the various building systems follows the necessary path that each system must take to reach its desired location. Must of this routing is determined by the design from the architect and structural engineer.

Common constraints that determine routing locations are the building structure, corridors, shear walls, fire walls, major equipment locations, and architectural requirements, such as ceiling type and interstitial space. The preliminary routing drawings reflect these constraints; each trade routes their system to their own advantage. This includes minimizing the length of branches and number of fittings, choosing prime locations for major components, routing close to support points, and designing for most efficient installation by their own trade.

2.6.2 Sequential comparison overlay process

The coordination process, as shown in Figure 4, begins with the all the specialty contractors bringing their preliminary drawings to a meeting. These drawings indicate the contractor's preferred routing or path that each branch of the system must take to reach desired locations and perform essential functions. This routing is constrained by the architectural and structural drawings, guided by the engineer's diagrammatic drawings, and selected by the contractor based on the lowest cost. It generally does not consider the other systems.

Figure 2. Current Process of MEP coordination using light table

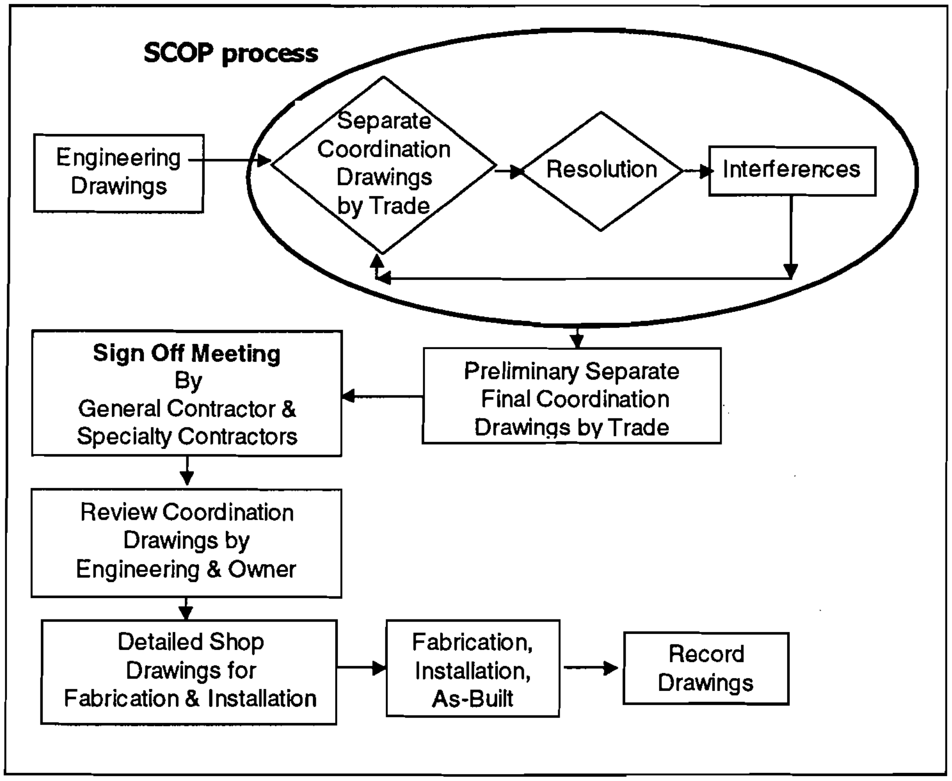


Table 3. Priority order for sequential comparison process

System (in priority order)	Priority/Special Notes
Mechanical (HVAC Dry)	usually first due to large size of components
Mechanical (HVAC Wet)	follows HVAC Dry due to interdependency of these systems
Plumbing (gravity driven systems)	design criteria for slope essential for system performance
Plumbing (pressure driven systems)	lower priority because less difficult to re-route
Process piping	takes first priority if critical to manufacturing process
Fire Protection	flexible routing within safety and architectural requirements
Electrical	most flexible routing, especially small diameter conduit
Control systems	flexible routing but must limit bend radius for pneumatic tubes
Telephone/Datacom	flexible routing but must limit bend radius for fiber optic cables

During the coordination meetings, the process begins with all the specialty contractors involved comparing their individual building systems. There is a sequence of overlaying of the multiple trades that takes place during these meetings.

The HVAC dry system is commonly used as a base. It is laid down first on the light table to be compared with all other trades. This is done because the HVAC dry system has the largest components and is hardest to relocate. The duct can be routed in only a few locations.

The HVAC wet system is the first system to be laid down over the HVAC dry system because it directly feeds into the HVAC dry system; the HVAC dry and HVAC wet system work together and must be tightly coordinated. In actuality, the HVAC wet system routing is based on the HVAC dry system routing and location.

The third system to become involved in the coordination process is the plumbing system. This includes all graded lines, waste lines, vents lines etc. Because of the stringent requirements of the gravity driven lines, the plumbing system is compared with the HVAC dry system. The gravity drain lines are typically graded at 1/8" for every one foot fall. This requirement forces the drain lines to compete with the large HVAC dry ducts at the higher elevations. The gravity drain lines must start up high so that they are able to make grade without falling below the ceiling tiles. The HVAC dry duct must also be located at higher elevations due to the large space requirements.

The next system in the coordination process is the fire protection system. The fire protection system is a pressure driven system; however, the main fire protection lines must be slightly graded to allow the system to be drained on a regular basis. This complicates the coordination of the main lines. The fire protection system is compared with the HVAC dry, HVAC wet, and plumbing on an individual basis.

The last system in the coordination process is the electrical system. The electrical system the most flexible of all the major systems.

Upon completion of the coordination process, all specialty contractors involved (mechanical, electrical, plumbing, and fire protection) sign-off on each others individual drawings. This sign-off is used to indicate that a particular drawing has been coordinated with the other trades.

Following MEP coordination, the specialty contractors 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. QC 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 markup and editing of the shop drawings or by consolidation of electronic files.

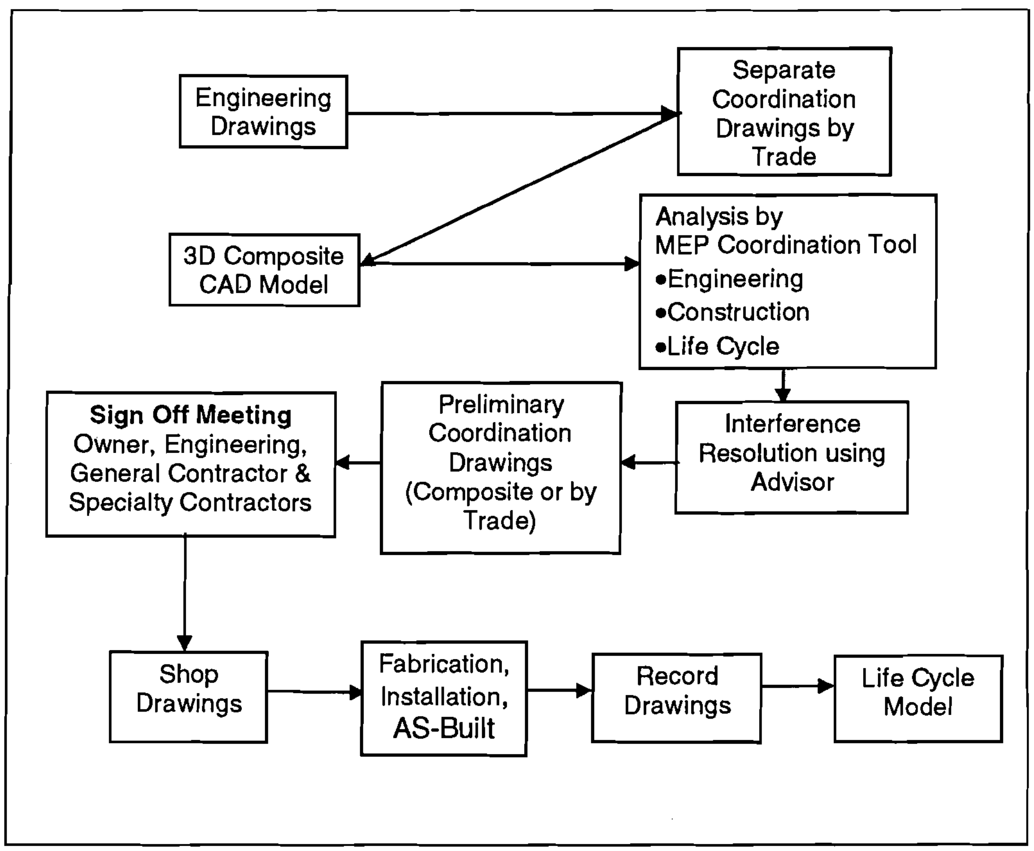
Chapter 3: Specifications for the MEP Coordination Tool

Based on the findings regarding the current process for MEP coordination, this chapter describes a possible revised work process using a computer tool. It also gives specifications for the tool.

3.1 Revised work process and tool for MEP coordination

An improved work process for MEP coordination will need to recognize the constraints of current industry organization by continuing the separate design of systems by specialty contractors but could nevertheless take advantage of the capability provided by a computer tool. A possible revised process, as shown in Figure 5, would start with separate CAD files routing each of the systems, combine these in a 3D CAD model, analyze this composite model to identify physical interferences and nonconformances with different types of design criteria, record decisions by experts to coordinate the systems, and produce separate layers or drawings for fabrication and installation by the different specialty contractors.

Figure 3. MEP coordination using tool



To implement this revised process, the tool will include capability for the following steps and types of analysis and checking in support of the MEP coordination process:

- verify that the routing of all systems fits within the architectural and structural constraints and avoids physical interferences between MEP systems
- verify compliance with design requirements for system functionality, such as slope for drainage, separation of water and electrical systems, or less than 360 total degrees of bends in conduit to allow cable pulling
- assure compliance with priorities for system location in MEP coordination, such as which system is routed "high and tight" for first installation and easier support
- provide material staging areas and access paths to allow the use of the most beneficial construction methods
- reserving "halos" or access paths for operation and maintenance.

The increasing capability of available hardware and software offers the potential to develop a tool for MEP coordination that includes the full range of capabilities shown in Table 5. This would allow active consideration of the three project phases shown in the table during MEP coordination. The revised work process using the tool for MEP coordination would also provide the equivalent of a plant design model for buildings – a major potential advantage for facility management, operation, and maintenance.

Table 4. Capabilities of MEP Coordination Tool

Project phase	System capabilities and output
design and coordination	• suggest priority rules for routing • allow sequential comparison process of trades' work • reserve space for access during construction and operation • indicate ripple effects of changes; perform local interference checking • identify relationships, e.g., water line routed above electrical equipment • determine location and size of wall and floor penetrations • provide advice concerning constructibility, operations, maintenance • store technical data for objects: design intent, specs, RFI's, quality documents • provide trial routing for standard offsets and branches • estimate space requirements for MEP systems
installation and testing	• indicate access and space available for installation • provide views to support coordination of installation operations • highlight sequence constraints from configuration • suggest installation sequence; link with 4D planning • calculate quantities and durations for estimates and schedules • indicate status from design to acceptance • indicate engineering holds and required releases for installation • indicate start-up system for all components
operation and maintenance	• provide direct access to operation and maintenance information for components • suggest access paths for operation and maintenance • index quality documentation

The hardware and software needed to provide the capabilities shown in Table 5 are now available; acquiring and representing the required knowledge remains the major challenge.

The specification for a software application developed in this research includes priorities for the type of systems included in the model and the level of detail (scope), the analysis performed and capabilities of the tool, the output and support for different activities related to the system over its lifecycle, and other features and capabilities. For each of these parts of the specification, the following sections list high, medium, and low priorities for the tool. The first section gives our initial concept for the tool.

3.2 Initial concept for the tool

Our initial concept for the tool was an Autocad 3D application that would assign layers to different systems. The model would begin with the architect's and structural engineer's models of the building or plant and add each of the systems considered in MEP coordination.

Much more than just a composite CAD model, the horizontal integration tool would represent the systems in a manner that allows rapid model development and easy visualization and checking to assure that all system criteria are satisfied. The following are examples of possible features that we initially thought the tool could include:

- prior space allocation to architect, structural engineer, and all contractors
- library of standard configurations that are frequently used, such as valve stations or piping for HVAC coils
- ability to highlight system features that require special consideration in coordination decisions, such as slope for drainage, access requirements for maintenance, and even aesthetic requirements for exposed systems
- ability to identify standard designs for wall and floor penetrations for MEP
- Internet links to import 2D or 3D models of systems and build a composite CAD model as designers or contractors locate systems.

These are examples of beneficial features for a horizontal integration tool custom tailored to the needs of MEP coordination. They came from discussions with industry professionals as a part of preparing the proposal for this research.

3.3 Scope of application for MEP coordination tool

Based on the information obtained from the multiple sources described in Chapters 2 and 3, we defined requirements for a horizontal integration tool in three categories: scope of application, analysis and capability, and support capability. The following table summarizes high, medium, and low priority items for the scope of application of the tool for MEP coordination.

Table 5. Scope for application of the tool for MEP coordination

High priority scope items	Medium priority scope items	Low priority scope items
apply during the early design phases include all major systems: capture CSA for interference and support; show required penetrations, flag requirements for architectural and structural represent the disciplines/trades who do not participate in coordination take different types of CAD inputs; help those not using CAD	contain the full model required for effective coordination handle special configurations, such as bus duct, valves, control boxes in duct reserve space for operation and maintenance; provide "halos" apply to buildings and plants provide space for branching and supports indicate locations of all connections to equipment, lab furniture, etc. consider weight and seismic supports incorporate vendor information for all equipment and components of systems	capture rules for design and routing and other restraints on installation capture craft experience capture knowledge for allowable solutions to frequent coordination problems, such as changes in duct sizes, rerouting electrical raceway, penetrations in the middle third of beams capture contractual responsibility for supply and installation of system components

Table 6. Analytical capabilities of the tool for MEP coordination

High priority analysis	Medium priority analysis	Low priority analysis
serve as space management tool; reserve space for each discipline/trade handle necessary change well support visualization of design configuration, system aesthetics, construction sequence provide real time feedback regarding full implications of coordination decisions cut sections or "MRI" at any location and in any direction in the building or plant	identify interferences help identify problems and support for resolution allow special attention to congested areas, such as around the building core; detail a congested area like a mockup display only those systems or layers currently under discussion support rapid engineering response to problems, replacing the slow RFI process consider installation sequence identify and evaluate relationships between components in the same and different systems, such as vertical alignment of components, penetrations through walls and floors, and segregation of water and power lines	operate on large screen so that experts in each discipline and trade can easily visualize and evaluate 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 check design compliance calculate the cost of changes in design or coordination calculate the schedule impact of changes in design or coordination highlight the implications of design requirements in excess of code

	consider and support shared knowledge between disciplines and trades perform calculations to precisely locate system components, considering insulation and other attachments not bog down the computer; take to the field on a laptop allow single data entry	

Table 7. Output of the tool for MEP coordination

High priority scope items	Medium priority scope items	Low priority scope items
support system design and detailing for fabrication support field coordination and detailed planning	support plan check and inspection by regulatory agencies produce required as-built drawings provide information for installation; highlight sequence and other constraints created by coordination decisions, such as the need to complete drywall before installation systems routed in close proximity	display system status link with a 4D planner or other visualization tools

Chapter 4 Knowledge for MEP Coordination

The knowledge contained by the MEP coordination tool is the most critical factor for its effectiveness. This knowledge is represented as characteristics of objects and applied to identify several types of problems with preliminary designs and possibly give advice regarding solutions that would satisfy the multiple constraints. It also allows the tool to identify detailed criteria that the coordinated MEP design must satisfy. The knowledge that the tool applies to identify and assist in resolving problems in MEP coordination includes design requirements, construction requirements, and knowledge related to the remainder of the facility lifecycle. Although the most visible parts of MEP coordination focus on the geometry and functionality of the systems, perhaps the greatest value added by the process relates to construction, operation, and maintenance of the systems.

During the first phase of this research we focused on the geometric aspects of MEP coordination, but also began acquiring knowledge concerning other design constraints, construction of the system, and the remainder of the facility lifecycle. This section summarizes the results of early knowledge acquisition regarding MEP coordination. We plan to greatly expand the knowledge base during continuing investigation of MEP coordination.

4.1 Design knowledge

Design knowledge is applied during MEP coordination to assure that the systems satisfy performance requirements for the specific project and comply with codes and standards. Design engineers and detailers bring design knowledge regarding each type of system to the MEP coordination process. This includes function, routing priority, relationship with other components in the facility, location and configuration. Examples of these types of design knowledge are:

- function, e.g., slope graded lines to flow, locate lighting fixtures to avoid obstructing lighting, locate sprinklers to cover areas, locate duct outlets for proper airflow, separate hot items, allow for thermal expansion
- priority for routing, e.g., from HVAC dry as highest to electrical conduit as lowest
- location, e.g., route systems requiring seismic or weight support for large loads “high and tight,” or close to the beams or slab above to satisfy code requirements for clearance, and to support fabrication and layout in the field
- relationship, e.g., systems routed directly below others require trapeze hangers; codes prohibit routing water lines above electrical equipment
- configuration: components per vendor data, ductwork per industry standards and aspect ratio, straight runs for flowmeters, pipe bends, branches from pipes, thermal insulation, bends less than 360 degrees in conduit, minimum radius for bends in fiber optic cables.

4.2 Construction knowledge

Construction knowledge is applied during MEP coordination to assure the feasibility of building the system and to increase the efficiency of field operations. This type knowledge includes access requirements, preferred configuration, construction method, and safety. Superintendents, Foremen and engineers familiar with field operations provide this knowledge. Examples of construction knowledge for the MEP coordination tool are:

- access requirement, e.g., provide path and halo (free space around system component) for construction craftspersons, materials, and construction equipment
- configuration, e.g., use standard materials and configurations, allow prefabrication offsite or in yard areas at the site; allow desired installation sequence, minimize fittings and field connections
- construction method, e.g., maximize prefabrication, allow efficient material handling, provide space and access for electrical cable pulling
- safety, e.g., minimize high time, avoid exposure, provide permanent scaffolding

4.3 Knowledge related to the remainder of the project lifecycle

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 to add these constraints to the coordination of MEP systems comes from facility managers, building engineers, and the maintenance staff. Examples of lifecycle knowledge identified to date for use in the MEP coordination tool are:

- testing and commissioning: support desired priority and sequence; allow isolation of subsystems
- operation: provide vents and drains, access to valves, instruments, and controls
- maintenance: provide access to filters, fire dampers, and controls; allow rebalancing

Further development of the tool, as described in the next chapter, will involve representation of additional knowledge that we have already acquired and acquisition of further knowledge. This will emphasize knowledge related to construction and the remainder of the project lifecycle.

Chapter 5: Acquiring Knowledge and Developing a Tool for MEP Coordination

Developing the tool for MEP coordination first required defining its essential capabilities, as described in Chapter 3. This specification evolved as a result of input from the Industry Advisory Group for the project (Appendix XX), knowledge acquisition, and development of the initial tool. This chapter describes these two key activities.

5.1 Acquiring and representing knowledge for MEP coordination

5.1.1 Knowledge acquisition

Our first step in knowledge acquisition was interviews with engineers, general contractors, specialty contractors, and operators. From these interviews we gained an understanding of the overall approach and process used for MEP coordination on different types of projects. We also obtained information concerning the typical level of design definition prior to coordination for different types of facilities and systems, the expectations and methods of approaching different design disciplines and construction trades, frequent problem areas, likely conflicts during coordination, and ways to avoid and resolve problems.

Our primary method of acquiring the detailed knowledge for the MEP coordination tool is attending coordination meetings. The coordination meetings provided case studies of MEP coordination on specific projects. Typically moderated by a representative from the general contractor and sometimes including a representative from the mechanical and electrical design engineer, these main purpose of these meetings was to complete the sequential comparison overlay process. Representatives from each of the specialty contractors are the main participants in the meetings. They do the overlay, identify the problems, and negotiate to resolve them. We collected the following types of knowledge at these meetings:

- types and implications of the constraints from other parts of the building design, including architecture, building codes, structural engineering, fire protection, and other special requirements
- design information (typically preliminary shop drawings) and knowledge of installation operations by their trades that the representatives from the specialty contractors typically bring to the meetings
- attributes of specific objects in different types of systems, including physical configuration and functional restrictions
- detailed steps in the sequential comparison overlay process, priorities for the different types of systems and reasons for these priorities
- specific types of problems and how they are identified and resolved

- small group processes to identify the problems, decide who must change to resolve them, and assess the cost and schedule impact and possible need for contract modification.

We have also gained very valuable insights regarding the knowledge required for MEP coordination from meetings of the industry advisory group for the research project. This includes approximately 25 members who represent architects, engineers, general contractors, and specialty contractors. The types of knowledge gained during meetings of the group include descriptions of current practice and reasons for the processes used, types of knowledge to include with the tool, priority needs for possible capabilities of a tool for MEP coordination, and types and areas of facilities that present special challenges for MEP coordination.

5.1.2 Knowledge representation

We are representing the knowledge in an object hierarchy and slot tables for each object in the design. This structure contains the knowledge needed to perform the functions of the tool, including identifying physical and functional interferences. The highest level categories in the knowledge hierarchy are spaces, functions, adjacency, and components. The specific MEP systems form the next level in the components category, including HVAC dry, HVAC wet, plumbing, fire protection, and electrical. Different types of components within each of the systems extend the hierarchy to the next level. For example, plumbing components include gravity lines and pressure lines and electrical components include bus duct and lighting.

The tool collects detailed characteristics for each object in a slot table (Table 9). Examples of this information include location coordinates, function in the system, spatial relation with other systems, functional incompatibility with other systems, dimensions, materials, and reasoning and recommendations concerning priority for location.

Table 8. Knowledge representation in slot table

Slot Edit View Instrument Options

	SupplyAirDuct1
Analyze!	'?Components.Analyze!
CheckROOM!	'?Components.CheckROOM!
CheckTOP!	'?Components.CheckTOP!
Cost_per_ft	5
Draw!	'?Components.Draw!
Function	carryair@MEP
HALO_required	1.5
Incompatibility(mv)	
InitializeValues!	'?Components.InitializeValues!
Interfers(mv)	
IsLocatedIn	C1@MEP
Material	Sheetmetal
OntopOF(mv)	Light1@MEP
Recommend!	'?Components.Recommend!
SlotsToInitialize(mv)	Interfers, Xmax ...
Temp	SupplyAirDuct1@MEP
Xmax	3.5
Xmin	1.5
Ymax	100
Ymin	0
Zmax	10.67
Zmin	9.67

5.2 Developing the tool for MEP coordination

5.2.1 Prototype tool

We developed a prototype tool for MEP coordination in the first phase of this research. We represented the knowledge by object hierarchy and slot tables in the Power Model software. The programming focused on methods and rules to perform the analysis of preliminary designs and provide feedback in the MEP coordination tool.

The current version of the prototype tool includes capability for entry of component data to define selected types of MEP systems. This prototype tool can develop cross section and plan views and analyze by system and area. The analysis identifies physical interferences and other violations of the characteristics established for the objects, such as blocking illumination paths from light fixtures. The tool facilitates relocating objects to resolve physical and functional interferences and reanalyzing the area to verify conformance with all required characteristics of objects. Analysis by the current version of the tool demonstrates the ability to apply knowledge concerning design criteria for the system to different configurations of the system and provide feedback concerning parts of the system that do not comply with the constraints.

The prototype tool has several performance limitations that further development will resolve. These include the requirement to input each object and limit its shape to a rectilinear 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).

5.2.2 Future development

Our next steps in developing the tool will focus on adding knowledge concerning construction and operations and maintenance. We will also add links to CAD software for input and output, seeking compatibility with AutoCAD, Bentley, and software used by specialty contractors, such as Quick Pen for mechanical work. As a part of these interfaces, we plan to provide a capability for the coordination tool to receive and transmit information over the Internet. This will allow developing a composite 3D CAD model that combines preliminary designs for each system and allows analysis by the coordination tool.

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. The 3D composite CAD model will include the capability to specifically locate interferences and to separate the coordinated design of each trade's work.

The completed tool will emphasize problem identification over recommendations for solution. For problems identified, it will fully define the location and type of problem, including source of the violated criterion. Using the tool, the process for MEP coordination will continue to rely primarily on the experience and creativity of the engineers and specialty contractors involved in MEP coordination for alternatives and solutions.

Longer term, the tool can provide the greatest benefit if it supports design decisions very early in the project, such as during the schematic stage for buildings. If the specialty contractors are involved early in a project, they can 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 assignment of space 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. Future versions of our tool for MEP coordination should support this by forecasting space requirements for these rooms and analyzing the implications of different space allocations.

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. Further development of the tool will add the capability 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.

Our future research activities will also include establishing 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 a common reference point for all design disciplines and trades to use. This will allow using the composite model of MEP systems for analysis by the tool as layers added to the architectural and structural design. We also plan to revise the entry of component data to follow as closely as possible the current practice for definition of systems in each of the trades. Examples include dimensioning supplemental steel from column lines and using invert elevation and diameter to define piping.

5.3 Testing and validating the tool for MEP coordination

To date, our testing of the tool has focused on verifying the following capabilities:

- input of the characteristics needed to define the systems and allow application of the knowledge to provide advice regarding trial locations
- analysis of test configurations to verify ability to identify physical interferences and violations of design constraints
- ability to revise the configuration to resolve the problem and analyze the new design to verify that the problems are resolved.

We plan further testing and validation following the additional knowledge acquisition and representation described above. This will include demonstrating the ability to provide advice concerning design, construction, and the remainder of the life cycle. We plan to compare the product of MEP coordination using the tool for advice on a real project with the design selected by the experts involved in the current process of sequential comparison.

Chapter 6: Preliminary Conclusions and Recommendations

This project highlights the opportunity and the challenge in developing a new work process and tool to improve performance of an important design and construction activity. 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 process of sequential comparison is slow and expensive. The active systems are increasing in complexity, scope, and portion of the critical path and budget for many types of buildings. Although plant design systems used on industrial projects can easily capture the geometric aspects of MEP systems, several practical considerations limit their use on complex buildings and light industrial plants. Primarily, the design and construction are fragmented between specialty firms and some of the systems require details known only to the fabricator to select the final configuration.

These challenges create a major opportunity to improve project performance using a revised work process for MEP coordination. These 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 computer capability to provide advice based on this expertise.

Progress to date on this research project indicates that it is feasible to capture knowledge concerning MEP coordination and represent it in a tool to analyze preliminary designs and assist with coordination decisions. The current prototype system can recognize interferences with other systems and with space reserved for future activities. It can also highlight violations to other types of design constraints, such as required separation or other relationship between components. Although the current version of the system focuses on satisfying design criteria, addition of constraints related to installation, operation, and maintenance appears feasible and is planned.

For industry, implementation of commercial software with the capabilities that we plan to demonstrate in the MEP coordination tool will result in faster, better, and less costly MEP coordination. This will enable engineers, designers, and specialty contractors to better achieve project objectives. The tool will also allow earlier application of knowledge to improve vertical integration. Perhaps the greatest benefit from a tool for MEP coordination will be the 3D CAD model for many other uses during the entire lifecycle of the facility.

For future researchers, the results of this project will increase understanding of design for functionality of MEP systems, construction, operation and maintenance. The knowledge acquired during this research and the planned recommendations for future work will support additional further development of product and process models for different types of building systems.

The researchers greatly appreciated support from Stanford's Center for Integrated Facility Engineering for the initial phases of this research. The Sloan Foundation, through the Future Professors of Manufacturing Program at Stanford, is supporting further development of the tool. We would also like to thank the many progressive design and construction firms that challenged and assisted us as members of the industry advisory group for the research.

other possible conclusions

Reasons for, advantages, limitations of current practice for MEP coordination

Information requirements for fabrication and installation include ..

These requirements are currently satisfied by .... coordination drawings ...

Information technology can improve the current approach by...

What would have to change to implement new technology? Expected benefits?

Effective MEP coordination requires detailed knowledge of codes and design criteria, system design, installation operations, and operation and maintenance of the systems.

Immediate feedback regarding the impact of coordination decisions on other disciplines and trades is a major need to improve the process.

Current PC's are not capable of running interference checks on even a small CAD model.

The major advantages and disadvantages of the current approach are ... need to accelerate

The need for increased visualization in current approaches for MEP coordination include...

Computer tools for MEP coordination are not likely to reduce the engineering scope for specialty contractors. Increased capability at this level may further shift detailed design from engineers to contractors.

Improving MEP coordination requires major changes in the division of responsibility and the work process in addition to the software tools used.

The effectiveness of current processes for MEP coordination depends greatly on the shared knowledge and working relationships of the designers from each of the specialty contractors involved.

The performance of currently available hardware and software severely limits the use of information technology for MEP coordination. The limitations include ...

Definition and allocation of design responsibility and scope is a fundamental problem. Who designs and who details what? This blurs the line between design and coordination. It also creates murky liability. Who is the EOR?

The engineer typically provides different levels of detail for different disciplines and size of components; from electrical as the least to duct as the most.

There are many needs for different information from MEP coordination; matrix of information vs user over the life cycle.

If the owner wants in excess of code, the engineer must design more.

MEP coordination is a great example of construction as an information business.

Coordination takes a long time now; depends on each contractor to do own part and then check against all of the others. Need to define how much coordination the designer does, CSA and MEP.

other issues to address in paper

Determining factors driving: industrial vs. building

People involved in each stage of coordination.

What are determining factors for installation sequence: an entire project, specific area of the facility?

Problems with current practice

Historical accounts of MEP coordination

Notes about general arrangement and preparation of drawings

Level of detailed required on drawings to coordinate MEP systems.

Level of effort placed in bidding and estimating for different trades.

Different types of information required for the following stages: Installation, Design, Validation, Fabrication, Documentation

Responsibility of Design consultant (Design vs. coordination): Where does the coordination responsibility of the design consultant end? How much of the coordination responsibility is placed on the specialty contractors?

other topics from TK proposal

objectives for coordination process and inputs from the perspective of the owner/operator, engineer, general contractor, specialty contractor

construction drawings from MEP engineers are diagramatic; various Architects, Engineers, and projects differ regarding issue of revisions to the drawings to keep up with RFI's

current software used, relevant capabilities, how used, e.g., Quick Pen, Autocad

the coordination drawings, often prepared by the HVAC dry contractor, contain a block for signoff by each of the other trades

contractors use their own shop drawings for fabrication and installation

examples of typical contract language (mechanical specs) regarding coordination, possibly in an appendix

comments from regulatory agencies may greatly impact MEP coordination

changes made during MEP coordination generally do not alter flow calculations for systems

differences between conceptual, schematic, construction, and shop drawings, possible with example figures or an appendix

need for and use of vendor information in various types of drawings

importance of MEP systems in buildings, capital cost, space required, operating cost

contrast the process in design-build and design-bid-build projects

Appendix A: Background for the Research

Background for MEP Coordination

Very limited published information is available concerning MEP coordination. Ongoing research to develop advanced planning tools relates to MEP coordination. Mahoney (1990) found limited early use of 3D CAD for design and coordination of mechanical systems. Fischer (1997) captured constructibility knowledge and developed a prototype system to evaluate the constructibility of a building structure as described by a preliminary a 3D model. This research demonstrated the feasibility of using process knowledge from downstream project phases for high-leverage decisions earlier in the project.

Several CAD systems are now used in the design of MEP systems. AutoCAD is the most widely used but specialized software is often used for mechanical systems. A number of these packages include interference checkers but they do not operate on a common CAD model. We found very limited use of object-oriented CAD systems, mainly for standard valves and fittings.

Current practice for MEP coordination and the problems identified above create many opportunities to improve and needs for information technology. To gain acceptance, an improved process for MEP coordination must solve or decrease the problems in the current process listed above. This need calls for application of information technology tailored to constraints of these projects. Object-oriented CAD databases could provide necessary information for design, procurement, fabrication, installation, commissioning, operation, maintenance. A tool for MEP coordination should also take advantage of potential for information exchange over the Internet. Visualization capability to provide any view of any location at any scale is another highly desirable feature. An effective tool for MEP coordination would provide the capability for instantaneous analysis and response regarding the implications of a proposed change. Another highly desirable feature is use of more powerful hardware for interference checking or more selective use of existing hardware to analyze changed parts of the systems.

MEP coordination and related software

Several CAD systems are now used in the design of MEP systems. AutoCAD is the most widely used but specialized software is often used for mechanical systems. A number of these packages include interference checkers but they are very slow and do not operate on a common CAD model. We found very limited use of object-oriented CAD systems, mainly for standard valves and fittings.

Commercial auto-routing software

Two firms provide software and consulting services for automated pipe routing.

Automated routing presents three options: network configuration from service to source, routing in free space, and channel routing. Most systems regularize within rectangular coordinates. Decomposition is essential. User interface is a major challenge.

The router provided by Design Power has found beneficial application in early estimating.

Relation to other CIFE research

This research strongly supports CIFE's integration goals and extends the potential application of CIFE's results to critical MEP systems in complex buildings and manufacturing plants that now do not utilize CAD models and object databases. These systems are the major determinants or detriments to project success for many types of facilities. This research directly relates to four CIFE goals for integration: improving the flow of knowledge among team members, facilitating concurrent design and construction planning, capturing and communicating design intent, and linking the design model to field applications.

The business reality of fragmented expertise and responsibility for MEP systems among the specialty contractors requires improved integration of design and construction teams across time and space. The tool that we will develop in this research will integrate design activities and foster increased consideration of all phases in the facility lifecycle during critical early design decisions.

Developing the MEP coordination tool will provide improved product models and increased knowledge of construction processes for use in CIFE's 4D CAD work. Other possible extensions and applications of the MEP coordination tool to other CIFE work include developing communication tools for preliminary designs, decision-making tools for MEP coordination meetings, visualization and planning tools for construction coordination meetings at the project site, progress monitoring tools, collection of record drawings, and maintenance planning tools. As a part of phase one of this research, we are providing input for a MEP test case of 4D CAD.

Kelly (93) identified the benefits of increased horizontal and vertical integration for meeting quality objectives on industrial projects. Garcia (93) developed a prototype system to automate the acquisition of design rationale for HVAC systems. This project highlighted the importance of knowledge regarding the constraints and context of design for subsequent design and operations decisions.

Mahoney (90) evaluated the potential to use 3D CAD to support multiple construction engineering activities on heavy and building projects. He identified several beneficial activities to define constructible design and tailor design information to best meet construction needs. Fischer (91) captured constructibility knowledge and developed a prototype system to evaluate the constructibility of a building structure as described by a preliminary a 3D model. This research demonstrated the feasibility of using process knowledge from downstream project phases for high-leverage decisions earlier in the project.

4D planning research

Appendix B. Industry Advisory Group for the Project

The industry advisory group identified in Table A1 forms a key part of the research team for this project. Individuals listed served on the IAG for phase one of the is project and have agreed to serve during phase two. Members of this group are involved in coordination-intensive projects, see the need to improve coordination processes, and are excited about this project.

The designers and contractors forming the group will also provide access to experts and projects during the time of coordination activities to allow data collection and will emphasize their information needs and expected results of MEP coordination. We also plan to involve software firms to identify characteristics of the coordination tools that will increase the potential for technology transfer by use of research results in new software products. Our IAG may provide a core group for a future sponsored project concerning MEP coordination.

Table A1. Industry advisory group for MEP project

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	Thema	HVAC design and coordination
Al Sahchez	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 approach, 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 a 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 the 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 client 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 problem solution.

Additional rules are needed to govern 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 varies 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 do 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' summary accurately describes 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 addition 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 these fall under the category of controls systems, they must 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, but inability been forced to delete this requirement because of inability to comply.
- 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. Thomas Korman 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 and 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 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 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 group suggested the specific actions listed above in continued knowledge acquisition and development of the tool. If possible, we will add a programmer to the research project to expedite addition of the new capabilities to the tool. Several members offered access to projects and staff experienced in MEP coordination to obtain further knowledge and test future versions of the tool.

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