Benefit-Cost Metrics for Design Coordination of Mechanical, Electrical, and Plumbing Systems in Multistory Buildings

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Abstract: Design coordination of mechanical, electrical, and plumbing (MEP) systems in buildings is a multidisciplinary effort to locate equipment, route distribution systems, and resolve interferences between systems that can cause field conflicts. Absent from existing research are defined metrics of design coordination—how much it costs to perform depending on project variables, and the true costs of field conflicts that are eliminated by coordination. This research was performed to explore the costs of design coordination in concert with the benefits of eliminating coordination conflicts that arise in the field. A standard method to measure costs of coordination is developed for case study projects. Potential variables that affect this cost are evaluated, and the negative impacts of field conflicts are measured. Project variables that have strong relationships with coordination costs are identified to be MEP density [MEP cost/square foot (SF)], and plenum height, and exploratory models to predict coordination costs using these variables are presented. Three distinct types of coordination conflicts are identified with measurable increasing impacts and cost. These results help to quantify the level of effort needed to coordinate building systems, and help to provide a basis for detecting projects that are likely to have problematic MEP coordination processes.

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Introduction

Planning spaces for mechanical, electrical, plumbing, (MEP) and fire protection systems in buildings is one of the most challenging and least defined aspects of the design process. Design coordination of MEP systems is a multidisciplinary effort to locate equipment and route distribution systems, such as ductwork and piping for each system. This requires coordination, not only among the specialty trades, but also with the building's structural and architectural systems. Design coordination of MEP systems can be challenging, especially on complex or mechanically intensive buildings and fast-tracked projects. Effective coordination of these processes avoids downstream field conflicts between building systems. The costs of field conflicts are difficult to predict and can vary depending on the timing and type of interference, the necessity to redesign systems, and the number of trades affected. As a result, the return on investments in coordination effort is difficult to quantify, and not surprisingly, not all contractors invest sufficiently in the process.

The goals of this research are to develop metrics that will help to quantify the costs and benefits of the MEP coordination process and to highlight the need to carry out this process with diligence. Specifically, the objectives of this research are: (1) to identify the key project and process characteristics that significantly affect the coordination process; (2) to develop a model for predicting coordination costs as a function of project characteristics; (3) to quantify the time, cost, and level of effort that are required to effectively perform MEP coordination; and (4) to explore the costs of field conflicts, or the costs of ***not*** performing coordination. This research also helps document the detrimental effects of building designs that leave insufficient space for MEP systems that result in costly coordination processes and potentially ineffective and unserviceable building systems. By defining and estimating the costs of coordination and the costs incurred when coordination is not performed, the value of diligent coordination is revealed, allowing for more informed decisions on the investments in MEP coordination.

Mechanical, Electrical, and Plumbing Costs: Existing Knowledge

MEP costs vary with the facility type and its unique system requirements. Tao et al. (2001) used MEP costs as a percentage of the total building cost to categorize projects as having high, medium, or low MEP costs, as shown in Table 1. Semiconductors and biotech plants are at the high end of the scale, but these

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J. Constr. Eng. Manage., 2005, 131(8): 877-889

Table 1. Classification of Building Types by the Cost of Mechanical, Electrical, and Plumbing (MEP) Systems (adapted from: Tao et al. 2001)

Facility type	MEP cost classification: High	Medium	Low
	MEP cost as percent of total building cost		
Semiconductor plants	60	50	40
Biotechnology plants	65	55	45
Heavy industrial plants	60	50	40
Multiresidential complexes	25	20	15
Commercial buildings	40	30	15
Research laboratories	50	40	30
Hospitals	50	40	30

projects are very limited in number, and often have deep interstitial spaces to accommodate the MEP equipment. Commercial buildings and residences are not typically MEP intensive compared to other building types. Research labs and hospitals are typically more constrained by space demands than industrial buildings designed solely to house equipment, and have consistently high MEP costs, accounting for at least 30 and up to 50% of total building costs.

Coordination Process: Current Practice and Related Literature

The MEP coordination process is usually outlined by general contractors in their contract documents. The team leader is often the heating, ventilation, and air conditioning contractor who designs large duct and piping layouts on the architectural background. Other systems are then added to this scale drawing.

Ideally, the coordination process uses a computer aided design (CAD) platform to detect and resolve interferences between systems. However, in many cases, a subcontractor's time and CAD resources are constrained, and coordination is conducted by the more conventional process of overlaying scaled transparent drawings on a light table and comparing them sequentially. In some cases, the process is not carried out at all.

A widely adopted MEP coordination process is described by Tatum et al. (2001) and characterized as the—sequential comparison overlay process. This process starts with the design of the system by designers, architects, and engineers. The design consultant assigns responsibility to the trade contractors to check for clearances, field conditions, and architectural constraints. Each trade generates shop drawings to its own advantage, choosing prime locations for their components, and locating runs to facilitate their own trade requirements. Representatives from each trade meet and indicate the proposed routing and location of their systems. Scale transparent drawings for each trade are overlapped on a light table, so that conflicts are apparent. The trade representatives then work together and reroute the systems and revise the drawings for optimal location and placement. In cases of major redesign, design engineers are asked for additional information and ultimately sign off and accept responsibility for design changes. This process is repeated and the product is a set of coordinated drawings, which they submit to the design engineer for approval. Next, shop drawings and cut sheets are generated for fabrication and the contractor's crews use the coordinated shop drawings for field installation. To complete the process, as-built drawings are prepared by marking or editing the shop drawings.

The schedule for coordination meetings is worked backward from the actual construction schedule. Ideally, there is a three-week gap between the coordination meeting signoffs and installation to allow for fabrication adjustments, field layout, and sequence planning. This lead time allows for the results of the coordination process to be full integrated into construction plans, and for the greatest value of the coordination effort to be gained by creating certainty in the dimensional location or embeds, hangers, and sequence of construction (Riley and Horman 2001).

Although it is a critical function of construction managers, very limited research has been performed that fully articulates the value, need, and process by which design coordination is performed for actual building projects. Detailed descriptions of four case studies are presented in Riley (2000). Riley discussed coordination as a critical part of the construction planning process, and described the benefits of the process and its effects on the field production. The paper identified the role of CAD in the process, the personnel required for the process and their key traits, the timing of the process, the coordination requirements for different facilities, systems to be included in the process, and the variable success of coordination efforts in avoiding field conflicts. It also provided an initial evaluation of how the costs of the coordination process can vary depending on delivery systems, and the range of conflict costs that can be expected on building projects.

Based on personal interviews and observation of experts in the field, Tatum and Korman (2001) documented the existing coordination processes of ten buildings of four types. The paper focused on development of a computer tool for integrating different computer MEP coordination software. Subsequent work by Korman et al. (2003) described an effort to develop a knowledge-based computer tool for identifying types of interferences and providing advice to resolve these coordination problems. This research focused on MEP systems for commercial and industrial buildings. The computer tool included determining the priority among different systems in different project phases, complying with geometric constraints, design intent, and constructability, and addressing end user and maintenance concerns.

In addition to the computer tools developed by Tatum and Korman (2001) and Korman et al. (2003), another useful result of their research is the identification and classification of knowledge required for MEP coordination. *Design knowledge*, or design criteria and intent, includes material considerations, support requirements, aesthetic considerations, insulation, and clearance requirements, and systems function and performance. *Construction knowledge* includes construction issues, such as sequencing, installation considerations, safety requirements, fabrication, and start-up and testing requirements. Finally, *operations and maintenance knowledge* relates to the remainder of the project life cycle, and includes expandability and retrofit requirements, accessibility, connection considerations, and safety considerations.

Costs and Benefits of Mechanical, Electrical, and Plumbing Coordination

Costs of coordination are largely comprised of the value time spent by various specialty contractors, engineering and architectural consultants, and management personnel, and are often hidden in the process of submitting, reviewing, and finalizing shop drawings. Riley and Horman (2001) conducted a pilot study of fourteen buildings, and explored the relationships among MEP coordination, conflict costs, and coordination costs, based on

J. Constr. Eng. Manage., 2005, 131(8): 877-889

Table 2. Coordination Effort for Four Case Study Projects

Project type	Project cost	Mechanical, electrical and plumbing coordination meeting (h/week)	Duration of coordination process
Classroom office	$7.5 million	4	1 month
Civic arena	$1.5 million	6	3 weeks
Library	$32 million	8	2 months
Laboratory	$40 million	20	6 months

project delivery systems. For the projects included in the study, coordination costs ranged from $70,000 to $290,000.

A successful design coordination process was defined by Riley and Horman (2001) as a prerequisite to a smooth progress of construction work, with logical sequencing and minimal interruptions to flow. As such, the primary benefit of MEP coordination is the avoidance of costs of field conflicts that should have been discovered during the coordination process. Hanna et al. (1999a,b) analyzed the effects of change orders caused by field conflicts on labor efficiency in the mechanical and electrical trades. The study included a database of 13 electrical contractors and 26 mechanical contractors. Their predictive model estimated loss in productivity as determined by the amount of change, schedule extension, timing of changes, and management experience in handling change orders. This research provides useful information on the impact of field conflicts to production.

Several field conflicts were observed in the case studies of Riley and Horman (2001), with the costs of change orders caused by field conflicts ranging from $1,500 to $60,000 per project. A formal link between costs of conflicts and coordination efforts was not possible because of the limited data, but projects in which extensive investments had been made in coordination efforts incurred much lower conflict costs. This work provided a step toward establishing a quantitative link between design coordination and the number and costs of field conflicts, and serves as the point of departure for the research reported here.

Data Collection and Analysis

The MEP design coordination process involves a number of people, including MEP coordination specialists, field personnel, and project managers. Accordingly, a variety of instruments were used to collect data, with each instrument tailored to suit the role of the targeted respondents. In the following sections, five different sets of data and their analysis are described.

Initial Case Studies

Case studies of four projects were used to guide future data collection efforts. The projects included a civic arena, a research lab, a classroom office building, and a library building. MEP coordinators on each project provided data on the amount of effort spent on coordination, shown in Table 2. Interviews with MEP coordinators revealed how the MEP coordination process varied among project types and contractors. In-depth knowledge of these four projects was used to narrow the scope of future research to laboratories and hospitals facilities, which were the most challenging projects in terms of MEP coordination.

Interviews helped to identify the types and extent of data needed for a model that would predict coordination costs. MEP coordinators helped to identify project features that influence the difficulty and cost of the coordination process. Among the relevant features are the project type, the density of MEP systems (in $/square foot), plenum height, and the timing of coordination. The complete list of relevant project characteristics is listed on Table 3 along with how features are specified and the justification for their inclusion in subsequent surveys. The importance ratings included in Table 3 will be explained below.

Survey of Project Managers

Findings from the initial case studies provided the basis for a questionnaire that was developed and administered to project managers. The questionnaire was sent to a total of 35 project managers working for five different major U.S. contractors on both the east and west coasts. Twelve complete responses were received. The survey included questions about the characteristics and process of design coordination for specific projects, and was divided into three parts. The first part collected general project characteristics, the second included information used to assess project coordination costs, and the third included an assessment of the timing and effectiveness of the coordination effort on the project.

Table 3. Project Features Affecting Coordination Efforts and Costs

Feature no.	Project feature (specification)	Importance rating	Justification
1	Type (usage of project)	7	Indicates the types and relative density of mechanical systems.
2	Project delivery system (CM/GC versus design-build)	5	Affect the timing and responsibility of coordination.
3	Contract type (lump sum versus GMP)	5	
4	Density of building (construction cost/gross SF)	6	Reflect the relative volume of MEP work on the project compared to other projects.
5	MEP density (MEP contract costs/gross SF)	8	
6	Intensity of MEP systems (MEP contract costs/SF/month)	8	Affects the rate at which construction will need to take place, and the time available to resolve conflicts.
7	Average floor-to-floor height, "FF" (feet)	8	Reflect the relative space available to fit MEP system in and around structural and architectural building elements.
8	Plenum height (FF height less floor height and structural system depth)	9	
9	Structure type (steel versus concrete)	6	
10	Timing of coordination (early or typical)	9	Reflects the ability of coordination problems to be detected and solved before they are found in the field.

Note: CM/GC=construction manager/general contractor; GMP=guarnateed maximum price; SF=square foot; MEP=mechanical, electrical, and plumbing; and FF=fixed fee.

J. Constr. Eng. Manage., 2005, 131(8): 877-889

Table 4. Project Characteristics and Costs Collected in Survey of Project Managers

Project characteristic	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Building usage	Research Lab	Research Lab	Research Lab	Research Lab	Research Lab	Hospital	Hospital	Hospital	Pharmaceutical Lab	Research Lab	Research Lab	Hospital
Project delivery system	CMR	CMA	CMR	P, CMR	DBB	CMR	DBB	CMA	DBB	CMR	CMA	CMR
Contract type	GMP	LS	GMP	GMP	LS	GMP	LS	GMP	GMP	Cost+fee	LS	GMP
Total construction cost ($ million)	26.63	92.00	21.00	8.2	169.50	44.00	5.50	6.66	17.00	15.30	228.00	1.20
MEP Contract costs ($ million)	8.14	18.60	10.66	5.50	88.93	12.95	3.40	2.97	9.00	5.99	104.50	0.59
Building density ($/SF)	223.81	191.67	348.91	241.18	331.71	176.00	135.14	154.81	1,133.33	329.35	231.94	266.67
MEP density (MEP $/SF)	68.39	38.75	177.03	161.76	170.51	51.80	83.54	69.07	600.00	129.03	106.00	131.11
MEP intensity ($/SF/month)	2.85	2.15	8.85	13.48	4.74	2.16	6.43	9.81	N/A	11.73	1.77	21.85
MEP costs as % of building cost	30.56%	20.22%	50.74%	67.07%	51.40%	29.43%	61.82%	44.61%	52.94%	39.18%	45.83%	49.17%
Ave. floor-floor height (feet)	15	15	14.67	14	15.75	14	12	12	20	15	14.5	12
Plenum height (feet)	6	6	4	4.5	16.75	6.33	2.5	10	20	9	4.5	2.5
Timing of coordination	Early	Early	Typical	Typical	Typical	Typical	Early	Early	Early	Typical	Typical	Early
Coordination	High	High	High	High	High	High	High	High	High	Above Ave.	Low	Typical
Coordination cost ($/SF)	0.88	1.03	1.80	1.89	1.28	0.40	0.94	0.55				

Note: CMR=CM@risk, DBB=design-bid-build; CMA=CM agency; P=preconstruction; GMP=guaranteed maximum price; LS=lump sum; MEP=mechanical, electrical, and plumbing; SF=square foot; and N/A=no data available.

Project Characteristics

Project characteristics were collected and quantified when possible so they could be compared to the coordination costs incurred for that project. Data included the type of project (hospital, research lab, or other), project costs (total building costs and MEP contract costs), the project delivery system, floor-to-floor and plenum height, specialty systems, other building characteristics, and construction sequencing. Selected variables are included in Table 4 for each of the 12 projects.

The 12 projects include 8 laboratories and 4 hospitals. Six projects had a construction management at risk delivery method, three with construction management agency, and three with design-bid-build as the delivery method. Seven projects had guaranteed maximum price as the contract type, four were lump sum, and one project had a cost-plus-fee contract structure. Building density ranged from $135 to $348 per square foot (SF), and MEP density ranged from $39 to $177 per SF. The cost of MEP systems varied between 20 and 67% of total building costs.

Coordination Costs

The second part of the survey included details of the coordination process (e.g., time spent in meetings, duration of entire process), and the number of team members involved. Data from the second part of the survey were used to estimate coordination costs. The first step was to identify the input of each member of the coordination teams, which included representatives from the owner-facility managers, operations and maintenance personnel, and representatives from architects and engineers/consultants. The general contractor/construction manager team included project managers, project engineers and MEP coordinators. The subcontractor teams included detailers, engineers, and foremen.

The costs of coordination were calculated as the product of the number of people from each of the categories above, the average time spent each week in meetings, total number of weeks they were involved and the average salary costs for the respective participants. The coordination costs were adjusted for the location of the projects and inflation over the construction period using indexes obtained from RS Means and specified per square foot so they could be compared among projects of different sizes in different areas and constructed over different periods of time. Projects P9 and P10 lacked information necessary to calculate coordination costs, and were omitted from the analysis. Coordination costs ranged between $0.40 and $1.89 per square foot, and are included in the last row of Table 4.

Coordination Timing and Effectiveness

Respondents were also asked to choose which of four possible levels best characterize the effort that went into the coordination process:

- **Level 1:** ***Low/Informal Effort***—Coordination was left to the subcontractor's discretion.
- **Level 2:** ***Typical Effort***—Typical effort was put into the process.
- **Level 3:** ***Above average effort***—Work was installed only after coordination is finished.
- **Level 4:** ***Detailed effort***—Floor slabs and overhead systems were not installed until coordination was finished, the coordination process extended into construction.

J. Constr. Eng. Manage., 2005, 131(8): 877-889

Table 5. Types of Coordination Conflicts, Timing of Detection, and Severity of Impact

Type	Time detected	Severity of impact
1	Detected and resolved before installation has begun.	Start of work is potentially delayed, redesign is required.
2	Detected after Trade 1 has completed work, Trade 2 forced to reroute work.	Trade 2: Disrupted and potential redesign and fabrication changes are required.
3	Detected after Trade 1 has completed work, Trade 2 forced to wait until Trade 1 moves work.	Trade 1: Disrupted, rework, and redesign required. Trade 2: Delayed.

Further, respondents were asked to describe the type of coordination process used, to provide examples of delays due to the timing and distribution of coordination effort and difficulties encountered during the coordination process, and whether the contractor felt that an inordinate amount of time was spent on the process.

Data on the timing and distribution of the coordination effort were used to create an indicator of whether the coordination was conducted early or late. Five stages of the building process were defined, and for each stage, the total time spent on coordination and the time spent by contractors were calculated using the information described above. Time spent by contractors was expressed as a percentage of total coordination effort for each stage and multiplied by a weight. The schematic design stage was weighted by 5, detailed design was weighted by 4, construction drawings by 3, bid award phase by 2 and the construction stage by 1—thus, earlier contractor involvement is weighted more heavily. The sum of the percentage involvement times the weights gives a project score. Projects scoring 10 or higher were rated as "early;" other projects were rated "typical."

Respondents were also asked to evaluate the coordination process and to identify field conflicts that resulted in major change orders. Each conflict was categorized in one of three distinct types, defined by the research team and described in Table 5. Information on the type, timing, reason, and trades involved for each conflict were used by the researchers to determine whether the project was suitable for comparison to other projects. Projects P11 and P12 were omitted because the coordination process had not been completed effectively and were therefore not representative of the effort the study is attempting to quantify.

Although the survey of project managers yielded only eight usable observations, they include enough detail to investigate relationships between project characteristics and coordination costs. This preliminary analysis was guided by responses from a second survey, described next.

Survey of Mechanical, Electrical, and Plumbing Coordinators

A second questionnaire was sent to 15 MEP coordinators with five general contractors/construction managers. Respondents were asked to rate the project features provided in Table 3 in terms of their importance in the MEP coordination process. Importance ratings were based on a scale ranging from 1 to 10, with 10 being the most important. Respondents were also asked to list other project characteristics which, in their opinion, affected the MEP coordination process and its costs. Ten responses were received. The average importance rating for each project characteristic is included in Table 3.

Project Features Affecting Mechanical, Electrical, and Plumbing Coordination Costs

Results from the survey of MEP coordinators indicate that *Plenum height* and *Timing of coordination* were the most important variables affecting coordination effort and costs, followed by *MEP density, MEP intensity, and Average floor-to-floor height*. Table 6 shows the Pearson correlation coefficients between project coordination costs and these variables for the eight projects described in Table 4. Although indicated as a critical feature of the success of coordination, the timing of the coordination process was not included in the analysis, as timing is a characteristic of the coordination process and not the building. In addition, the goal of the study was to identify the cost of a diligent coordination process, which, by definition, should take place prior to the construction of the superstructure, thus eliminating timing as a useful variable for predicting coordination costs. The Building Density variable (total construction cost per gross SF) was also included to investigate its relationships with other variables.

Although the data set is not large enough to draw detailed conclusions, the correlation coefficients provide insight into which variables were likely to have meaningful relationships to coordination costs. *Building density, MEP Density, MEP Intensity, and Plenum height* each yielded correlation coefficients with coordination costs above 0.5. *Average floor-floor height* had a correlation coefficient of 0.347 with coordination costs, and was omitted from further analysis since floor-to floor heights in buildings are highly variable, and often more directly related to architecture rather than MEP equipment. Fig. 1 shows coordination costs graphed against the four remaining variables.

Building density is highly correlated with coordination costs, as seen in Fig. 1(c). However, it was omitted from further analysis because it is influenced by many other project characteristics that are not related to MEP systems. *MEP intensity* (MEP costs/SF/day) is also highly correlated with coordination costs [Fig. 1(d)],

Table 6. Pearson Correlation Coefficients for Project Characteristics and Coordination Costs

Variable	Density	MEP density	MEP intensity	Ave. FL-FL height	Plenum height	Coordination costs
Density	1.000					
MEP density	**0.769**	1.000				
MEP intensity	0.286	**0.767**	1.000			
Ave. FL-FL height	0.625	0.104	−0.376	1.000		
Plenum height	−0.290	−0.451	−0.044	−0.154	1.000	
Coordination costs	**0.757**	**0.886**	**0.623**	0.347	**−0.556**	1.000

Note: MEP=mechanical, electrical, and plumbing; FL-FL=floor to floor.

J. Constr. Eng. Manage., 2005, 131(8): 877-889

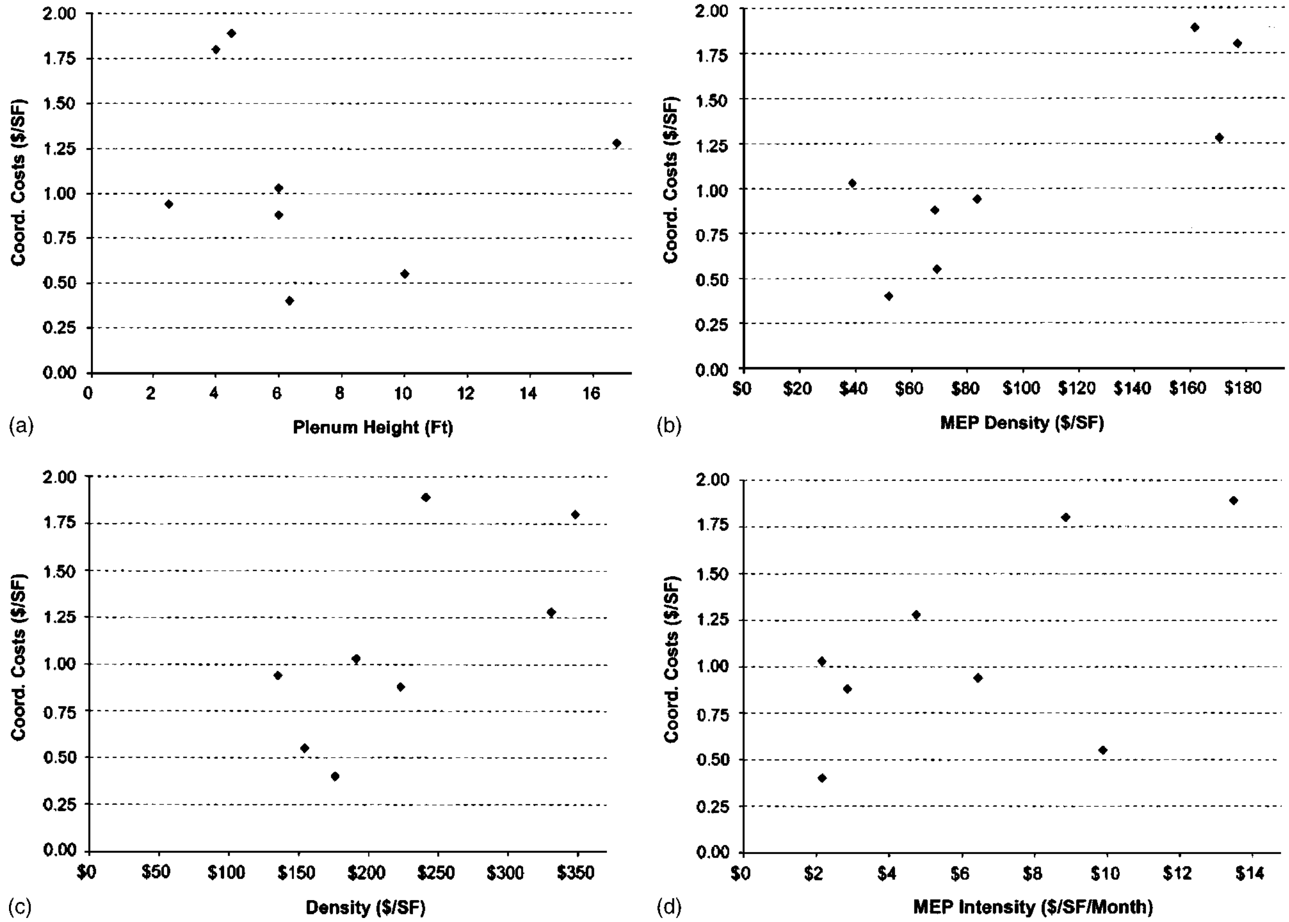

Fig. 1. Coordination costs and project characteristics

but it is also correlated with *MEP Density* and is sensitive to the project schedule. Therefore, it was also omitted from further analysis.

The two variables of greatest interest are *MEP density* and *Plenum height*. The graphs in Fig. 1 suggest that there may be a nonlinear relationship between each variable and coordination costs. This is logical when considering the extreme case of these two project features. Decreasing the plenum height squeezes MEP systems, and can result in an increased number of complex coordination problems that will be challenging to resolve. In several early cases, project team members described very tight plenum spaces as a particular challenge to the coordination process. At the same time, increasing MEP density indicates a greater volume of distribution piping and ductwork, increasing the likelihood of complex coordination problems that will take time and resources to resolve. Based on this preliminary analysis, these two variables were the subject of a more detailed follow-up investigation, described next.

Collection of Additional Coordination Cost Data

Coordination costs, plenum height, and MEP density were collected for an additional 37 multistory laboratories and healthcare facilities. These data were collected from one contractor who maintained detailed accounting of time spent on coordination costs, and are included in Table 7. Only projects that satisfied the "*Level 4—Detailed Coordination Effort*" criteria described above were included in this analysis. Coordination costs for these projects varied between approximately $0.46 and $1.98/SF. The projects had a range of MEP density between $18 and $56/SF and plenum heights between 2.2 and 5.2 feet.

Figs. 2 and 3 show coordination costs, plenum height, and MEP density of the 37 projects. Nonlinear relationships between coordination costs and plenum height (Fig. 2) and coordination costs and MEP density (Fig. 3) are evident. Since these data were based on records of actual coordination costs rather than the calculation used on the first eight projects, the new data set was analyzed independently for potential relationship between plenum height, MEP density, and coordination cost.

Predicating Coordination Costs

Two simple models of coordination costs were estimated using ordinary least-squares regression. The first specified coordination costs as a linear function of plenum height and MEP density, and the second included those variables and their squared values. Data used to estimate the regression equations are included in the first six columns of Table 7, and the regression results are included in Table 8.

Both regression models indicate a statistically significant relationship between coordination costs and the project characteristics (plenum height and MEP density). In the linear model, both coefficients are statistically significant, with p values less than 0.01. Overall, the model fit well, with an adjusted R square of 0.78, and an F statistic indicating overall statistical significance of the model (p value <0.01). Not surprisingly, the polynomial regres-

J. Constr. Eng. Manage., 2005, 131(8): 877-889

Table 7. Data Used in Regression Analysis of Coordination Costs

Project no.	Coordination cost ($/SF)	MEP density ($/SF)	Plenum height (feet)	MEP density squared	Plenum height squared	Polynomial model: Predicted coordination costs	Polynomial model: Error	Polynomial model: Error as % of actual	Linear model: Predicted coordination costs	Linear model: Error	Linear model: Error as % of actual
28	0.46	23	3.8	529	14.4	0.58	−0.12	25.91	0.68	−0.22	47.63
10	0.46	39	4.1	1,521	16.8	0.70	−0.24	52.47	0.69	−0.23	49.31
11	0.47	36	5.2	1,296	27.0	0.51	−0.04	8.72	0.22	0.25	54.22
29	0.56	18	3.4	324	11.6	0.66	−0.10	18.07	0.80	−0.24	43.08
16	0.56	22	3.8	484	14.4	0.56	0.00	0.79	0.67	−0.11	19.82
9	0.58	26	4.2	676	17.6	0.50	0.08	13.13	0.54	0.04	6.77
24	0.59	25	4.6	625	21.2	0.41	0.18	30.59	0.37	0.22	37.29
27	0.61	16	3.8	256	14.4	0.47	0.14	22.59	0.62	−0.01	2.03
15	0.62	34	3.6	1,156	13.0	0.81	−0.19	29.89	0.85	−0.23	37.03
12	0.63	34	3.6	1,156	13.0	0.81	−0.18	27.83	0.85	−0.22	34.86
30	0.63	42	4.3	1,764	18.5	0.69	−0.06	9.10	0.63	0.00	0.03
8	0.64	45	3.6	2,025	13.0	0.94	−0.30	46.56	0.94	−0.30	46.68
4	0.67	41	4.2	1,681	17.6	0.70	−0.03	4.37	0.66	0.01	1.14
18	0.69	15	3.2	225	10.2	0.71	−0.02	2.50	0.86	−0.17	24.39
5	0.71	32	4.2	1,024	17.6	0.59	0.12	17.41	0.59	0.12	16.99
23	0.75	28	3.2	784	10.2	0.90	−0.15	20.24	0.96	−0.21	28.49
2	0.76	32	2.8	1,024	7.8	1.17	−0.41	54.21	1.16	−0.40	52.46
13	0.80	35	2.9	1,225	8.4	1.15	−0.35	44.19	1.14	−0.34	42.80
32	0.81	41	4.0	1,681	16.0	0.75	0.06	6.94	0.74	0.07	8.19
19	0.82	34	3.2	1,156	10.2	0.98	−0.16	19.80	1.01	−0.19	23.45
6	0.93	31	3.1	961	9.6	0.99	−0.06	6.79	1.03	−0.10	10.60
26	0.94	29	3.4	841	11.6	0.82	0.12	12.53	0.89	0.05	5.28
17	0.98	22	3.5	484	12.3	0.68	0.30	30.72	0.79	0.19	19.08
1	1.10	21	3.1	441	9.6	0.85	0.25	22.66	0.95	0.15	13.86
31	1.14	37	2.7	1,369	7.3	1.30	−0.16	13.72	1.24	−0.10	8.77
14	1.20	34	3.3	1,156	10.9	0.93	0.27	22.13	0.97	0.23	19.03
22	1.32	45	2.6	2,025	6.8	1.45	−0.13	10.10	1.35	−0.03	1.93
25	1.48	35	2.8	1,225	7.6	1.24	0.24	16.16	1.20	0.28	18.69
20	1.52	48	2.6	2,304	6.8	1.49	0.03	2.23	1.37	0.15	9.88
33	1.55	46	3.1	2,116	9.6	1.18	0.37	24.10	1.15	0.40	25.79
3	1.64	42	2.3	1,764	5.3	1.62	0.02	1.16	1.44	0.20	12.00
36	1.79	85	2.3	7,225	5.3	1.97	−0.18	10.22	1.79	0.00	0.09
35	1.81	60	2.8	3,600	7.8	1.48	0.33	18.22	1.39	0.42	23.44
7	1.83	54	2.6	2,916	6.8	1.55	0.28	15.45	1.42	0.41	22.49
37	1.91	76	2.4	5,776	5.8	1.85	0.06	2.92	1.68	0.23	12.14
21	1.97	150	2.2	22,500	4.8	2.01	−0.04	2.03	2.36	−0.39	19.76
34	1.98	110	2.5	12,100	6.3	1.90	0.08	4.22	1.91	0.07	3.59
Minimum	0.46	15	2.2	225	4.8	0.41	−0.41	0.79	0.22	−0.40	0.03
Maximum	1.98	150	5.2	22,500	27.0	2.01	0.37	54.21	2.36	0.42	54.22
Average	1.02	42	3.3	2,417	11.5	1.02	0.00	18.13	1.02	0.00	21.71

Note: MEP=mechanical, electrical, and plumbing; and SF=square foot.

J. Constr. Eng. Manage., 2005, 131(8): 877-889

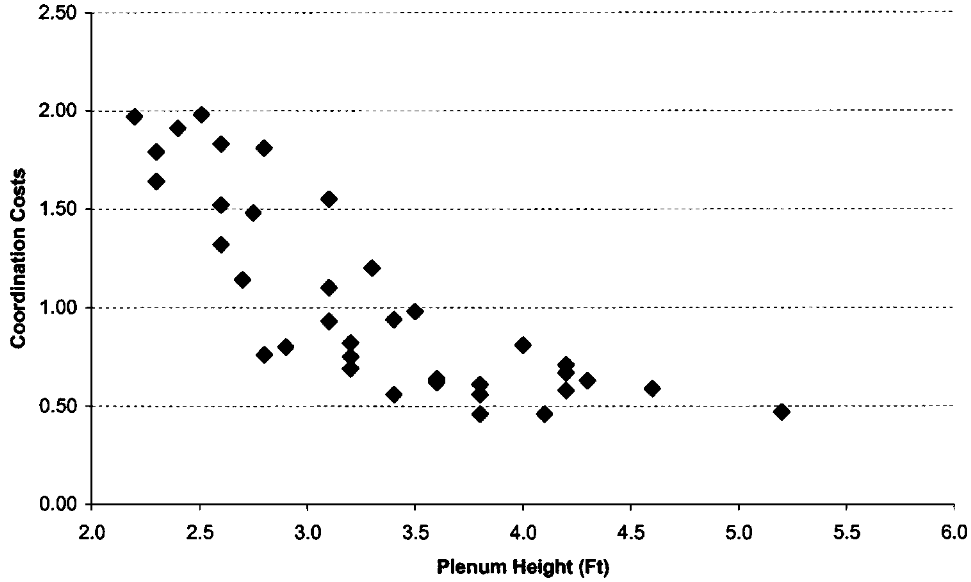

Fig. 2. Plenum height versus coordination costs for additional data set

sion model shows a better fit. Both squared terms are statistically significantly different from zero (p values <0.10), and the adjusted R square of this model is 0.83.

Based on the regression results, the two predictive models are:

1. Linear Model

$$\text{CCost} = 2.0380 + 0.0081(\text{MEPD}) - 0.4067(\text{PH})$$

2. Second-Order Polynomial Model

$$\text{CCost} = 3.2627 + 0.0184(\text{MEPD}) - 0.00008(\text{MEPD})^2 - 1.2676(\text{PH}) + 0.1213(\text{PH})^2$$

where Cost=coordination cost per square foot; MEPD=MEP density in \$/SF; and PH=Plenum height in feet.

The predicted coordination costs for each project are included in Table 7, along with the percentage error in the prediction.

Discussion

The regression analysis produced two simple models for predicting coordination cost. Although the polynomial model fits the data better, the differences between the two models are small. The polynomial is probably more accurate in the extreme ranges of MEP density and plenum height since it accounts for nonlinear relationships. However, the linear model is reasonably accurate and may be a more practical option due to its relative simplicity.

Figs. 4 and 5 show the actual and predicted coordination costs plotted against plenum height and MEP density. In each figure, diamonds represent the observed coordination costs. The predicted value (from the polynomial model) associated with each observation is represented by a horizontal dash and connected to the actual value. Thus, the height of the connecting lines indicates the magnitude of the prediction error.

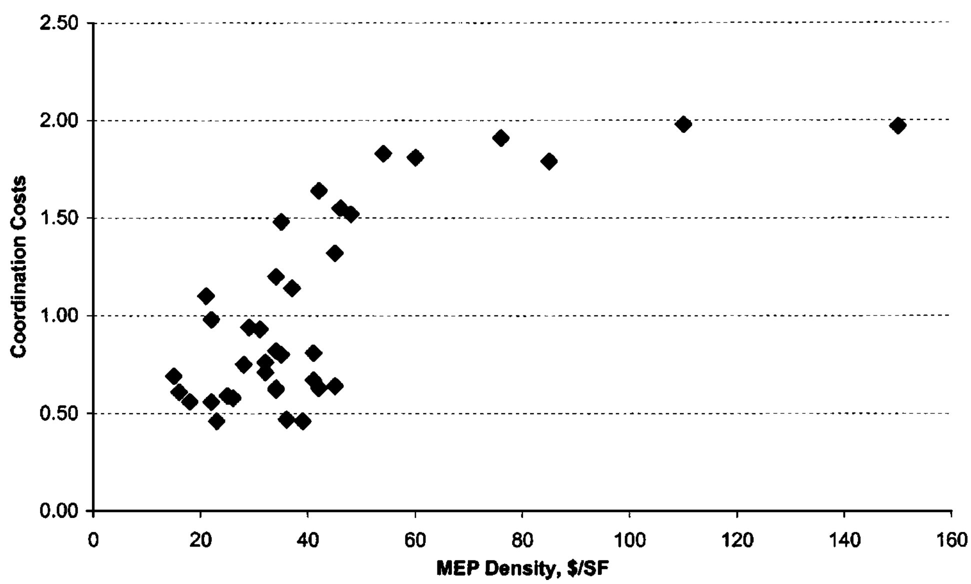

Fig. 3. Mechanical, electrical, and plumbing density versus coordination costs for additional data set

J. Constr. Eng. Manage., 2005, 131(8): 877-889

Table 8. Summary of Coordination Cost Regression Models

Explanatory variable	Linear model	Polynomial model
	Estimated coefficient (p value for null hypothesis that coefficient equals zero)	
Intercept	2.0380 (0.0000)	3.2627 (0.0027)
MEP density	0.0081 (0.0000)	0.0184 (0.0017)
MEP density squared		−0.0001(0.0165)
Plenum height	0.4067 (0.0000)	−1.2676 (0.0201)
Plenum height squared		0.1213 (0.0957)
Adjusted $R2$	0.7769	0.8255
F statistic for overall fit (p value for null hypothesis that all coefficients equal zero)	63.67 (0.0000)	43.57 (0.0000)

Note: MEP = mechanical, electrical, and plumbing.

It is important to note that the predictive models are based only on the two variables that demonstrated the strongest relationship to coordination costs. Many variables, such as the timing of coordination, project size, and project complexity, are not included in the model. It is also important to note that the coordination cost data used came from a single contractor, and that other methods of accounting for coordination cost may yield different results.

Despite these limitations, the models provide a useful tool for comparing projects, and for schematic estimation of coordination costs. The results of the model were also used to investigate how changes in MEP density or plenum height would be expected to change coordination costs. Figs. 6 and 7 show the expected changes in coordination costs from changing plenum height and MEP density, as predicted by the linear and polynomial models, using the mean of each dependent variable as a starting point. Using Fig. 6, a decrease in plenum of height of 18 in. from a mean of 3.3 ft (40 in.), would be expected to increase coordination costs by approximately \$1.0/SF. On a 50,000 SF laboratory project, this would mean an increase in coordination costs of \$50,000.

Survey of Foremen and Project Managers

A final questionnaire was written and administered to identify the type, occurrence, and cost of field conflicts. This one-page questionnaire was sent to project managers and foremen of specialty trades on projects in Southern California, Texas, and Washington D.C. Respondents were asked to identify conflicts that occurred, their timing, and the severity of their impact. In addition, they were provided with a list of potential effects of field conflicts from Hanna et al. (1999a,b)—including overmanning, schedule compression, overtime, space conflicts, material shortages, and loss of productivity—and respondents were asked to identify the effects of the conflicts they encountered.

Twenty sets of data were collected. Conflicts described by foremen and project managers were categorized into the conflict types described in Table 3. One-half of the conflicts reported were Type 1, which were detected during design. Thirty-three percent of conflicts were Type 2, which were detected during construction, and 17 percent were Type 3, the worst type in terms of potential production impacts. Since Types 2 and 3 conflicts are field detected, one-half of the conflicts were not detected by the coordination efforts on these projects.

Effects of Field Conflicts on Production

Foremen were asked to provide information about the specific effects of field conflicts. Fig. 8 shows the percentage of conflicts of each type that resulted in specific inefficiencies. The most common effect of Type 1 conflicts was schedule compression, which resulted from 79 percent of the Type 1 conflicts. Space conflicts, loss of management, extra coordination, and under manning were much less frequent, with each affecting less than 30% of Type 1 conflicts.

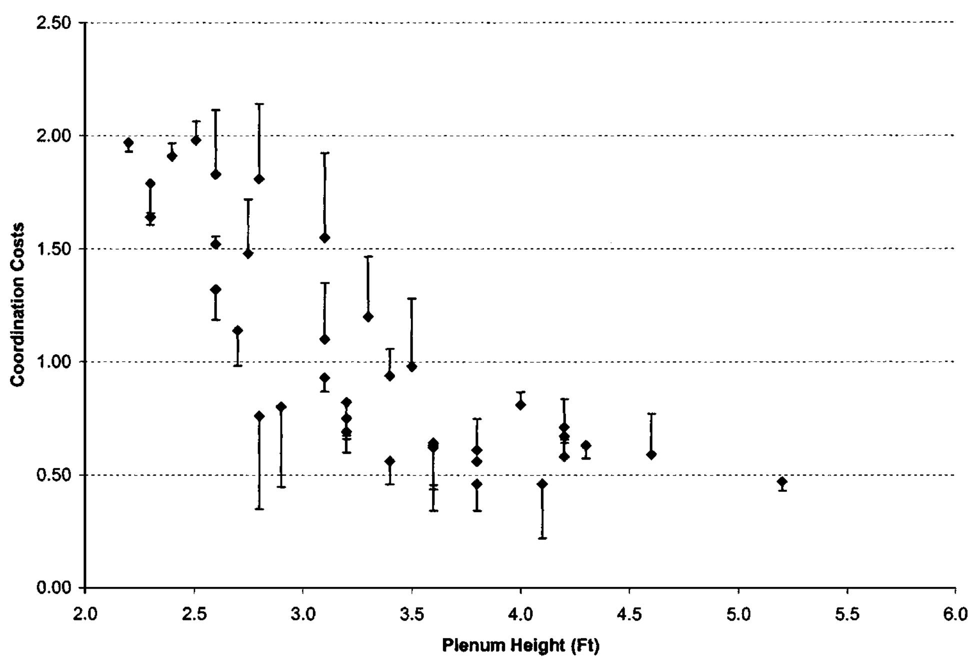

Fig. 4. Plenum height with observed coordination costs and costs predicted using polynomial regression model

J. Constr. Eng. Manage., 2005, 131(8): 877-889

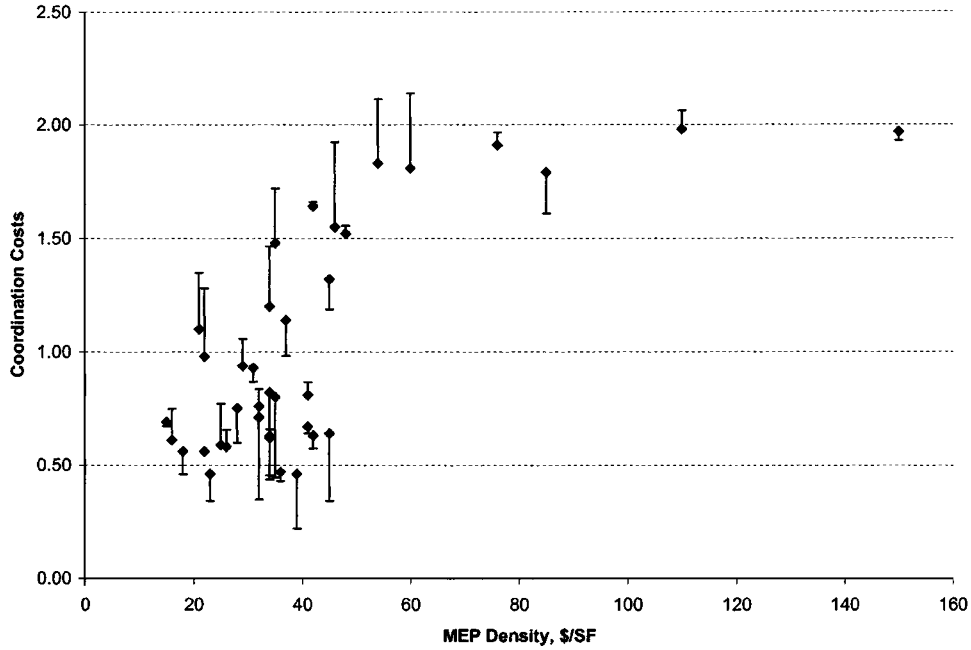

Fig. 5. Mechanical, electrical, and plumbing density with observed coordination costs and costs predicted using polynomial regression model

Occurrence of each effect was more frequent for Type 2 conflicts than for Type 1 conflicts, with the exception of schedule compression. Space conflicts, loss of productivity, and schedule compression were the most common, resulting from 84, 74, and 53% of Type 2 conflicts, respectively. Additional effects of Type 2 conflicts listed by foremen but not included in Fig. 8 include loss of preplanning hours, extra material costs, and added supervision.

Type 3 conflicts had the maximum impact, with every Type 3 conflict resulting in loss of productivity, and over one-half resulting in schedule compression (74%), space conflicts (63%), and overtime (63%). Other effects included lower crew morale and added supervision. In summary, the later a conflict arose, the more frequently negative effects were observed.

Costs of Field Conflicts

Project managers from both construction managers and mechanical contractors were then surveyed to obtain the average costs resulting from the three types of conflicts. Data from these sources were obtained directly from change order logs. The costs of conflicts were lowest for Type 1 and highest for Type 3 conflicts. Based on change order data, Type 1 costs varied between $0 and $1,000; Type 2 costs varied between $2,000 and $5000; and Type 3 costs varied between $3,000 and $30,000.

These conflict costs are based on change orders, but conflict costs are more hidden when a change order is not generated. Respondents were asked for the ratio of conflicts to change or-

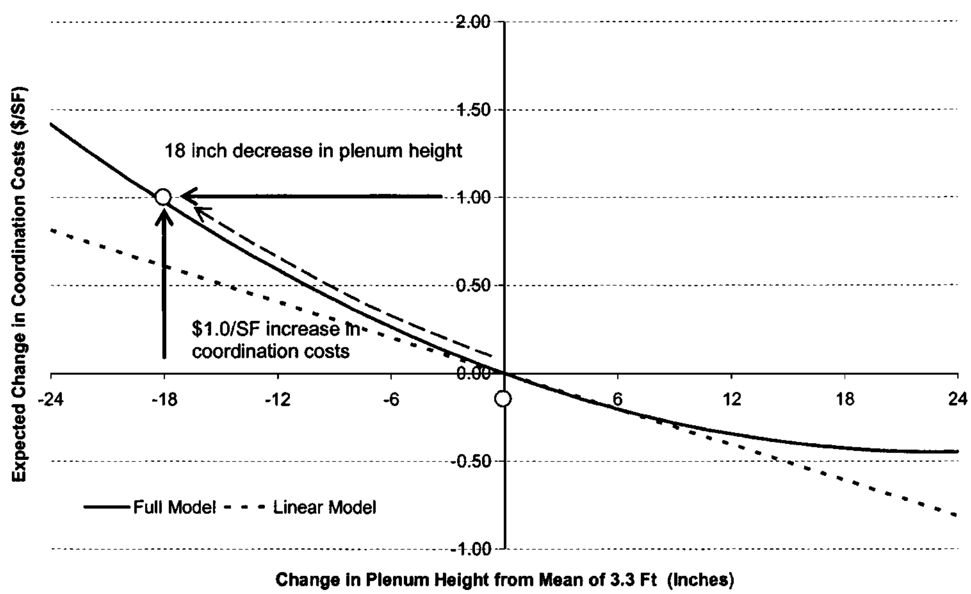

Fig. 6. Effect of plenum height on coordination costs

J. Constr. Eng. Manage., 2005, 131(8): 877-889

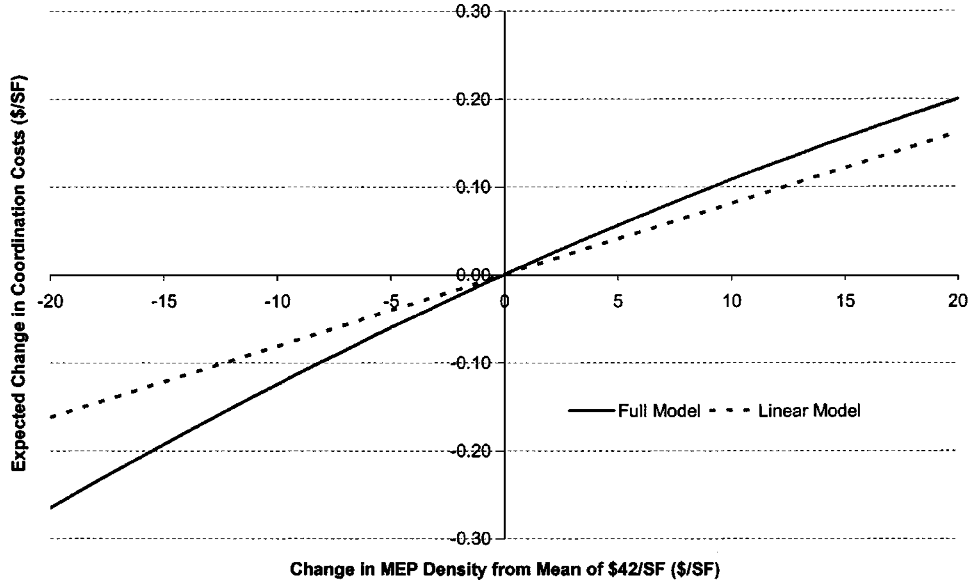

Fig. 7. Effect of mechanical, electrical, and plumbing density on coordination costs

ders, and this ratio ranged between zero and ten. On average, for every five field conflicts, only one resulted in cost recovery via a change order—in other words, costs of approximately *80% of the field conflicts are not recovered by contractors*.

Summary of Data Analysis

The data collected through this research provides an improved understanding of both the costs and benefits of MEP coordination processes. Table 9 summarizes the key metrics, associated variables, and range of values explored in this study. Definitions for variable levels of coordination effort were identified. These definitions can help provide a standard technique to characterize variable levels of coordination requirements.

Coordination costs were identified to range between $0.5 and $2.0/SF on laboratory and hospital projects. Plenum height and MEP system density were found to be useful variables in predicting coordination cost. Other key factors affecting the cost of coordination were identified by MEP coordinators as the type of project and the timing of coordination. Three types of field conflicts were defined based on the timing of their occurrence, the

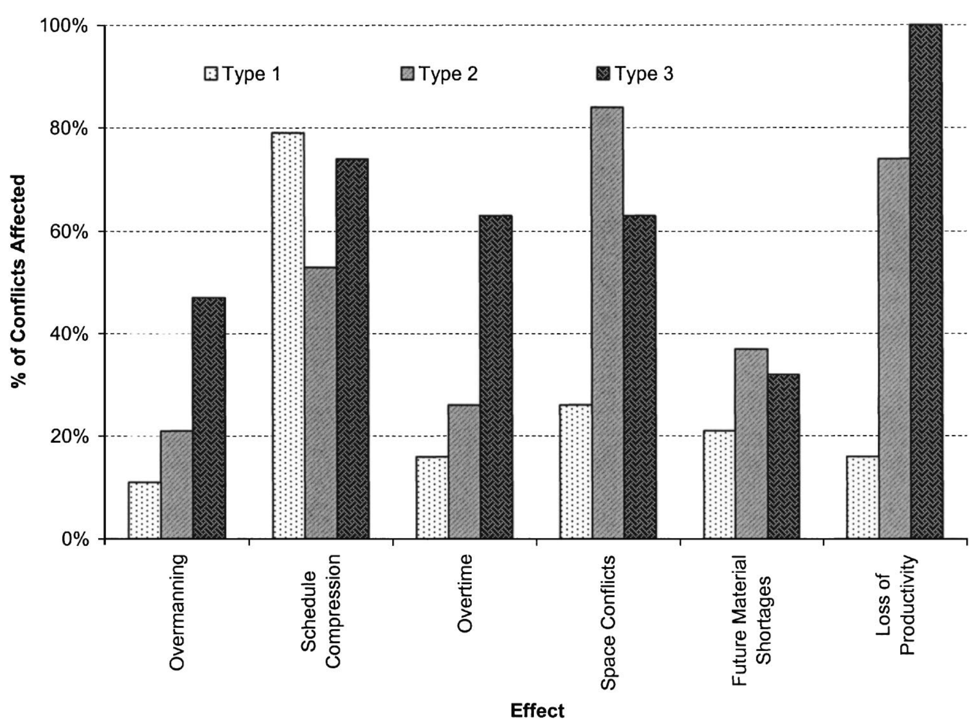

Fig. 8. Effects of Type 1, Type 2, and Type 3 conflicts

J. Constr. Eng. Manage., 2005, 131(8): 877-889

Table 9. Summary of Coordination Metrics

Metric/variable name	Description	Range of values found
Coordination effort		
Level 1—low/informal	Coordination was left to the subcontractors discretion.	Found on small projects with average schedules.
Level 2—typical	Typical effort put into the process.	Typical effort found in industry often leading to field conflicts.
Level 3—above average	Work is installed only after coordination is finished, coordination completed prior to construction.	Detailed efforts found but often not completed in time to avoid delays and field conflicts.
Level 4—detailed	Floor slabs and overhead systems were not installed until coordination is finished, the coordination process extended into construction.	Laboratory and Hospitals Projects with detailed coordination efforts were used as model projects in this research.
Types of conflicts		
Type 1	Detected and resolved before installation has begun (least impact on production).	- Cost range=$0–$1000. - Approx. 50% of all conflicts. - Typically occur at 5—15% complete.
Type 2	Detected after Trade 1 has completed work, Trade 2 forced to reroute work (moderate impact on production).	- Cost range=$2000–$5000. - Approx. 33% of all conflicts. - Typically occur at 15–50% complete.
Type 3	Detected after Trade 1 has completed work, Trade 2 forced to wait until Trade 1 moves work (severe impact on production).	- Cost range=$3000–$30,000. - Approx. 17% of all conflicts. - Typically occur at 60–80% complete.
Incident rate/change order	Number of field conflicts that result in formal change orders.	Average of 20% of conflicts result in change orders.
Predictive variables for MEP coordination costs		
Plenum height (PL)	Average height between bottom of structural frame and suspended/framed ceiling.	2.2–5.2 feet. mean=3.3 feet.
MEP density (MEPD)	Cost of MEP construction labor and materials/ gross SF of building area.	$18–$56/square foot mean=$42/SF.
Coordination cost	Cost of personnel and resources needed to perform coordination.	$0.5–$2.0/square foot.
Predictive polynomial model (R square=0.83)		
Coordination cost/SF	$=3.2627+0.0184(\mathrm{MEPD})-0.00008(\mathrm{MEPD})^2-1.2676(\mathrm{PH})+0.1213(\mathrm{PH})^2$	

Note: MEP=mechanical, electrical, and plumbing; and SF=square foot.

severity and distribution of their impacts, and the ranges of their cost. It was also found that, on average, only 20% of field conflicts that occur were formally charged as change orders.

Practical Applications

Results from this research show a useful correlation between the MEP coordination costs per square foot of building area and the easily calculated project variables of *plenum height* and *MEP density*. The basic model provided can help owners and contractors to predict coordination costs and the level of coordination effort that will likely be needed based on these variables. When combined with an increased awareness of the other factors that affect coordination costs, this model can also help quantify how small plenum heights result in inordinately high coordination costs.

The analysis of the types and occurrences of field conflicts also has practical value by providing a better understanding of the broader impacts of conflicts on projects, based on the timing of their occurrence. The research also sheds light on the fact that on average, less than one-half of actual conflicts result in change orders, and thus their costs are not directly recovered. This further highlights the practical advantage of avoiding conflicts through coordination. Finally, the distinctions made between the three types of conflicts as defined in the research can help to justify claims made based on poorly coordinated design drawings and resulting field conflicts.

Conclusion

This research defined key variables affecting the cost and level of effort needed to perform design coordination of MEP systems. The data collected in this study quantify the costs of MEP coordination and field conflicts. A regression model specifies the relationship between coordination costs and several project variables identified as a part of this study. The observed costs of field conflicts are substantial, lending support to the hypothesis that investments in coordination yield net gains by avoiding the costs of conflicts, particularly in projects with dense MEP requirements.

A complete cost-benefit analysis of investments in the design coordination process was not possible from these data, as all influential variables have not been characterized. Further, a complete analysis would incorporate the relationship between the number and type of conflicts on a project and various levels of coordination effort. Progress has been made on techniques to assess the costs and likely benefits of coordination for a more robust analysis in the future.

J. Constr. Eng. Manage., 2005, 131(8): 877-889

Appendix. Example Calculation of Coordination Cost on Case Study Projects

	Cost/hr		P1		Total cost (in $)
Design consultants					
Architectural (C1-No. of people C2-wh/week C3-No. of weeks)	41	1	0.5	12	245
Structural (C1-No. of people C2-wh/week C3-No. of weeks)	36	1	0.5	12	213
Mechanical (C1-No. of people C2-wh/week C3-No. of weeks)	38	1	2	12	923
Electrical (C1-No. of people C2-wh/week C3-No. of weeks)	40	1	2	12	968
Plumbing (C1-No. of people C2-wh/weeek C3-No. of weeks)	38	1	2	12	923
Fire protection (C1-No. of people C2-wh/weekC3-No. of weeks)	38	1	2	12	923
Total					4,196
General contractor/construction manager					
Project manger/engineer (C1-No. of people C2-wh/week C3-No. of weeks)	39	1	2	12	935
MEP coordinator (C1-No. of people C2-wh/week C3-No. of weeks)	39	1	16	12	7,482
Field superintendents (C1-No. of people C2-wh/week C3-No. of weeks)	32	1	16	12	6,144
Total					14,563
Specialty contractors					
HVAC-piping					
Detailers (C1-No. of people C2-wh/week C3-No. of weeks)	25	1	40	12	11,847
Engineers/Project Manager (C1-No. of people C2-wh/week C3-No. of weeks)	34	1	24	12	9,668
Foremen (C1-No. of people C2-wh/week C3-No. of weeks)	33	1	0	12	0
HVAC piping					21,517
HVAC-duct					21,517
Electrical					21,515
Plumbing					21,517
Fire protection					21,517
Other					0
Owner					0
Total costs					126,345
Location factor					0.82
Inflation					1.008
Total cost after adjustment					104,438

Note: MEP = mechanical, electrical, and plumbing; HVAC = heating, ventilation, and air conditioning.

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J. Constr. Eng. Manage., 2005, 131(8): 877-889