SCHEDULING MODEL CONSIDERING CONSTRUCTION INTERFACES FOR BUILDING PROJECTS

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Abstract: Practitioners often manage construction interfaces and scheduling separately. However, poor management of construction interfaces frequently causes delays in project duration. This work develops an innovative scheduling model that incorporates management of construction interfaces for building projects. The proposed model comprises five steps, including generating an integrated schedule, establishing interface work groups, identifying front- and post-holding activities for each work group, mapping interface events, and transforming to a construction interface based network schedule. The developed schedule network has fewer activities, links, and paths than the conventional schedule network, increasing readability and schedule control.

Keywords: Interface management, construction interface, network scheduling, and schedule control.

1. INTRODUCTION

Building construction project execution frequently involves several contractors, such as civil/ architect/structure (CSA), mechanical/electrical (M/E), etc. These contractors must perform certain construction activities to erect various physical objects (such as reinforcing steel, forms, pipes, and facility equipment) in particular locations or spaces. However, proper sequence arrangement of the activities and well-combined shop drawings of these objects are required in advance to avoid interface problems that may cause work disturbances during the erection of these objects. A work disturbance caused by an interface problem can be a stoppage of one activity to wait for another, degraded functions, a change request, or even a costly reworking [1]. An accumulation of disturbances for several activities may delay the entire project and increase the project cost. These consequential delays or extra costs are exaggerated when the project is complicated or involves numerous contractors.

Regarding interface management, most recent research has focused on construction space management, including site layout planning techniques for reducing space conflicts and scheduling techniques considering space constraints. For example, the MovePlan system [2] treats "space" as a resource to be attached to each activity in a construction schedule. The system enables the modeling of site space needs during project scheduling and space conflict on the site is eliminated by adjusting the schedule. Thabet and Beliveau [3] developed a scheduling model by quantifying workspace demand and availability parameters for multistory buildings. Riley and Sanvido [4] established a space planning method to identify the specific spaces needed for activities, define locations for these spaces on multistory building construction, develop a work sequence that defines the order in which spaces are occupied, and identify potential spatial conflicts. Finally, with particular reference to building facade interfaces, Pavitt and Gibb [5] discussed interface management in three categories — physical, contractual, and organizational, and then created an interactive software tool to provide a strategy for optimizing the technical and management aspects of cladding interfaces.

Although the management of construction interfaces has been recognized to significantly dominate construction duration performance, interface management and schedule control still are poorly linked in practice. Without definite scheduling information to support their intensive efforts, the field engineers do not know the deadline for resolving particular interface problems, and nor do they know which interface problems are more urgent than others for preventing delays or unnecessary costs. This study presents an innovative scheduling model that considers the construction interfaces for supporting both schedule control and interface management [6].

2. DEFINITION OF CONSTRUCTION INTERFACE

This study defines a construction interface as either a physical connection between two or more construction objects, a working contact between two or more object-erecting activities, or a constructability problem caused by poor design details or conflicting design information. Possible interface problems related to each type of construction interface are listed below:

- Physical connection. — The embedded connection is an example. Additionally, for example, pull boxes are attached to the finish of an interior wall (i.e., an "attached" interface); and M/E pipes cross with one another in a limited duct space (i.e., a "space interfering" interface) [1].
- Working contact. — Typical examples include the conflict in activity sequence, interruption of activity working path (e.g., large scale M/E equipment must be moved into a room before construction of that room is completed by the C/S/A), and competition for limited temporary working space (e.g., C/S/A's finish activity and M/E's equipment installation activity are performed in a room with limited space).
- Constructability problem. — For example, permanent room space is insufficient for accommodating multiple pieces of facility equipment; and difficulty arises in assembling construction components.

3. PROPOSED MODEL

Developing the proposed construction interface (CI) based scheduling model is an attempt to treat network activities identified as interfering with others as a single interface work group. Several work groups are established in the aforementioned integrated schedule. Figure 1 illustrates the implementation of this idea. The upper of Figure 1 displays a conventionally integrated schedule network with four individual schedules (prepared by four different contractors), and the bottom portion displays an established CI-based schedule network. This proposed model is detailed as follows: (1) major terminologies are defined, (2) typical interface problems in building construction are identified, and (3) the modeling steps are presented.

3.1 Interface work group, interface event, and holding activities

As shown in Figure 1, the CI-based scheduling model proposes a method of using interface work group (WG), interface event (IE), and holding activities to help represent construction interfaces in the schedule. An interface WG comprises a set of activities that are executed on the same building component (for example, a wall, slab, ceiling or girder) and/or are executed using the same working space (for example, a ceiling void or a room) within a short period. An interface WG can be viewed as a work package for managing the interface problems of a particular construction component or working space.

The activities in a WG are divided into three parts: a front-holding (FH) activity, one or more interface events (IEs) established by the in-between activities of the WG, and a post-holding (PH) activity. The FH and PH activities represent the start and end points of the WG, respectively. That is, an interface problem for a specific WG does not emerge until the FH activity starts, and will not be entirely resolved until the completion of the PH activity. When a WG comprises multiple IEs, additional middle FH and PH activities should be identified from the in-between activities.

The in-between activities of an IE are concurrently or sequentially executed and have several interfaces among them. Since these interfaces are interrelated, it is preferable to care for these interfaces as a whole, that is, a single event. Thus, from the management perspective, an IE can be treated as a small work package dealing with a particular set of interfaces. The interfaces between different IEs can be assumed to be uncorrelated. That is, IEs can be resolved individually.

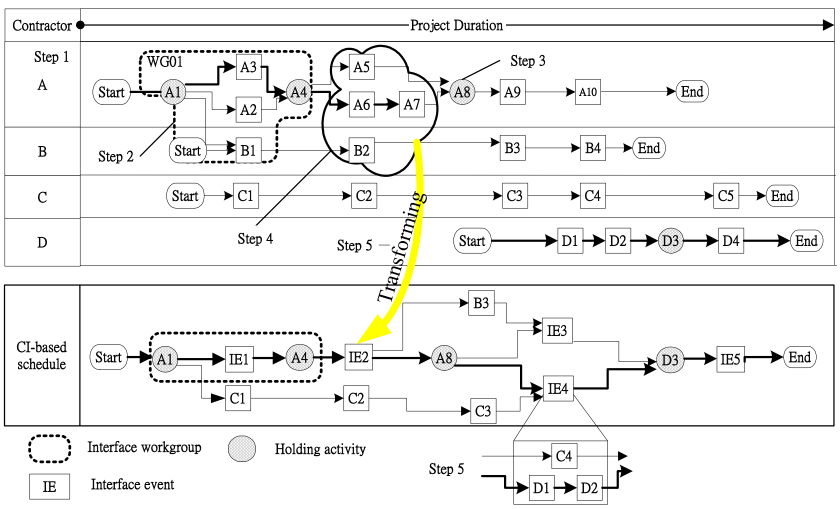

Figure 1. Idea of the CI-based scheduling model

3.2 Typical interface problems in building construction

Building project construction may be broadly divided into several stages, namely: site preparation, foundation construction, underground and upper structure, finish, and equipment installation. During the early stages, construction interface problems generally are minimal because the involved major activities (e.g., piling, slurry wall construction, and excavation) usually are performed by a single C/S/A contractor (who easily can resolve any interface problems among their subcontractors or trades) and the design details are less complex.

Structure related. In constructing certain structural components (such as columns, girders, beams, and slabs), interfaces frequently occur among C/S/A, M/E, and other contractors. For example, in pouring concrete for a floor slab, after completing a surveying activity (i.e., a FH activity), activities of placing bottom reinforcing steel, forming, placing cast-in sleeved pipes, plumbing, and placing top reinforcing steel (or top mesh) are performed sequentially or concurrently. The concrete can be poured only after these activities are completed. A delay in concrete pouring often results if the work of the M/E in placing cast-in sleeves and plumbing is not finished in time. Also, if the composition of the required shop drawings is poor, then a high density of placed cast-in sleeved pipes and electrical tubes is likely to be impossible to fully embed inside in the slab within a limited space (e.g., a slab with a thickness of only seven inches).

Finish related. The finishing for ceilings, walls, and slabs also is an area of common interface problems. For example, ceiling construction may include surveying, framing, stud setting, placement of electrical tubes, mechanical pipes (including fire protection plumbing, air conditioning ducts placing, and others) and first panel, lighting fixture installation, second panel placing, and painting. Usually, the work begins with surveying, moves on to first panel placement, and ends with painting. The completion of ceiling work thus can be divided into two parts here, namely the ceiling-1 and ceiling-2 interface events. Construction interface problems for the first IE (i.e., ceiling-1) mainly result from either the limited space (for installing high density of tubes, pipes, and ducts) or the complex activity sequences. A suitable composite shop drawing thus should be generated in advance to ensure that all construction materials can be installed in the ceiling. Additionally, contractors must negotiate an appropriate sequence (i.e., when to transfer the working space to another contractor, once a contractor has finished a particular part of his work). Further reworking after the completion of the first panel placing is not welcomed. After the first IE activities are completed, lighting fixtures, air conditioning system diffusers, and fire alarm sensors can be installed, followed by the second panels. Again, reworking after completing the ceiling painting is discouraged.

Equipment installation related. Interface problems may occur when installing equipment to a specific location, such as to an air conditioning (AC), electrical power (EP), or control center (CC) rooms. The issues related to this type of interface problem include the conflict between equipment move-in time or move-in path, limited space for accommodating equipment, and the constructability of physical connections between equipment and structural components.

First, equipment can be installed in a room either before or after room completion depending on equipment size. For example, large sized equipment generally must be placed in a room before the surrounding structure (namely, walls and ceiling) of the room is completed. Otherwise the door of the enclosed room would simply be too small for the equipment to pass through. Although disassembling-and-reassembling the equipment offers an alternative solution, this approach can compromise future equipment performance quality. Consequently, another common solution is for the C/S/A contractor to leave a temporary "hole" in the wall or ceiling during concrete reinforcement. After the equipment is moved in by the M/E contractor, the C/S/A contractor then closes the hole. In addition to this interrelated sequence (namely, C/S/A→M/E→C/S/A), the equipment move-in time (namely, when the equipment is moved into the room), move-in path, and move-in conditions for transferring the room between contractors have to be set in advance.

Second, some equipment-related interface problems arise because of specific room spaces being too small to accommodate all pieces of equipment. This problem can be resolved either by procuring different sized equipment or changing the room size. Third, certain equipment-related problems commonly exist in the physical connections between the structure and facility equipment.

3.3Modeling steps

The proposed CI-based scheduling model includes the following five steps (see Figure 1).

Step 1: Generating an integrated schedule. The construction of a building project often involves multiple subprojects. Since all subprojects must be completed for the entire building project to be useful, the management of the various subprojects preferably should be integrated. The schedules of these subprojects thus should be integrated into a single schedule. Such an integrated schedule can be established by connecting the activities of the individual schedules according to the logical relationships between activities. For example, M/E plumbing activity (say, activity A) cannot be started until C/S/A surveying activity (say, activity B) is finished, and must be completed before C/S/A concrete pouring activity (say, activity C) can be started. The links B→A and A→C thus can be established.

Step 2: Establishing interface work groups. This step involves establishing the interface WGs in the integrated schedule. For example, Figure 1 shows that activities A1, A2, A3, and A4 of contractor A, and activity B1 of contractor B are grouped to comprise WG01. Based on the previously analyzed typical interface problems in building construction, five typical interface WGs are identified (Table 1): the reinforced concrete (WG01) is structure related; the ceiling (WG02), wall (WG03), and raised slab (WG04) are finish related; and the equipment installation (WG05) is equipment installation related.

Table 1. Typical interface WGs, IEs, and holding activities in building construction

Construction stage	Work group	Building component	Type of IE	FH activity	Typical in-between activities	PH activity
Structure	WG01: Reinforced concrete	Column, girder, beam, slab	Column, girder, beam, slab	Surveying	Cast-in sleeved pipes placing, forming, reinforcing, plumbing	Concrete pouring
Finish	WG02: Ceiling	Ceiling	Ceiling-1	Surveying	Framing, stud setting, AC duct placing, place M/E tubes and pipes, first panel setting, lighting fixture installation	First panel placing
	WG02: Ceiling	Ceiling	Ceiling-2	First panel placing	lighting fixture installation, second panel placing	Painting
	WG03: Wall	Interior wall	Interior wall	Stud setting	First side panel placing, AC controller installing, electric pull box placing	Second side panel placing
	WG04: Raised slab	Raised floor	Raised slab	Surveying	Slab framing, AC duct placing, cable tray installing	Cover plate installing
Equipment Installation	WG05: Equipment installation	AC room, EP room, CC room	AC room, EP room, CC room	Ceiling painting, or second side panel placing of interior wall, or raised floor cover plate installing	Equipment base foundation, equipment components installing	Installing last piece of equipment

IE: interface event, FP: fire protection, AC: air conditioning, EP: electrical power, CC: control center.

Step 3: Identifying holding activities for each work group. Table 1 displays the FH and PH activities (as well as the IE and typical in-between activities) for each of the five defined WGs. For example, the surveying and concrete pouring activities are the FH and PH activities, respectively, for the reinforced concrete WG. Additionally, the PH activity of a WG can be the FH activity of anther WG.Notably, if a WG has more than one IE (e.g., the ceiling WG), additional FH and PH activities must be identified for confining the IEs. Should this be the case, the PH activity of an IE may be the FH activity of anther IE. For example, in Table 1, the activity of first panel placement plays the roles of the PH and FH activities for ceiling-1 and ceiling-2 IEs, respectively.

Step 4: Mapping the interface events. Once both holding activities for an interface WG are set, the rest of the in-between activities are tied together (called "mapping" herein) to form one or more IEs. Table 1 also lists the six typical IEs of the five identified WGs. Among these six IEs, two (i.e., ceiling-1 and ceiling-2) are related to the ceiling WG. As implied earlier, the ceiling WG is broken into two IEs because each IE can be managed independently without interfering with the other.

Step 5: Transforming to a CI-based network schedule. After determining the holding activities and IE(s) for each WG, the originally integrated schedule easily can be transformed to a CI-based schedule through the following sub-steps:(1) to represent each mapped IE as a single node. (2) To connect each IE to its predecessors (including FH activity) and successors (including PH activity). (3) to evaluate the duration of each IE. IE duration is determined by the longest path in the IE' subnet by applying the CPM forward and backward calculations to this CI-based network .

4. EXAMPLE DEMONSTRATION

Suppose a building construction project is divided into four subprojects that are performed by contractors A, B, C, and D, respectively. A total of 24 activities are associated with these schedules, that is, ten, four, five, and five activities for contractors A, B, C, and D, respectively

4.1Evaluation results

A CI-based schedule for this example project can be generated based on the following modeling steps.

Step 1: Generating an integrated schedule. After examining the interrelationships between these schedules, suppose an integrated time-scaled project schedule is established. Table 2 lists the network data (such as duration, logical sequence, ES, LS, EF, and LF) for each project activity. Based on the Critical Path Method (CPM) calculations, the project duration is 97 days, and the critical path is A1 → A2 → A4 → A6 → A7 → A8 → A9 → A10 → D1 → D2 → D3 → D4 → D5 (as indicated by the dark line in Figure2)

Step 2: Establishing interface WGs. Suppose four interface WGs of activities are established in the integrated schedule (see Figure 2). Activities A1, A2, A3, A4, and B1 are grouped in WG01; A8, A9, A10, B4, C4, D1, D2, and D3 are grouped in WG02; A4, A5, A6, A7, A8, B2, and B3 are grouped in WG03; and D3, D4, D5, and C5 in WG04.

Step 3: Identifying holding activities for each WG. As summarized in Table 3, activities A1, A4, A8, and D3 are identified as the FH activities for WG01, WG03, WG02, and WG04, respectively. Moreover, A4, A8, D3, and D5 are the PH activities for WG01, WG03, WG02, and WG04, respectively. In this example project, activities A4, A8, and D3 play the roles of both the FH and PH activities. Notably, in WG02 (including two IEs), A10 is the PH activity for IE3 and the FH activity for IE4.

Step 4: Mapping the IEs. In this example project, each WG consists of one or two IEs. That is, each of the WG01, WG03, and WG04 has an IE, namely, IE1, IE2, and IE5, respectively. Additionally, WG02 has two IEs, namely, IE3 and IE4. Table 3 shows the in-between activities for each IE. For example, IE1 for the WG01 has three concurrent activities, that is, A2, A3 and B1.

Step 5: Transforming to a CI-based network schedule. A CI-based schedule network can be established after representing each IE as a single node and connecting each IE to its predecessors and successors, as illustrated in Figure 3. The activities along the critical path (showed by the dark line in Figure 3) include A1, followed by IE1, A4, IE2, A8, IE3, A10, IE4, D3, IE5, and D5. Notably, each IE is on the critical path. Taking WG01 as an illustrative example, A1 and A4 are the FH and PH activities for IE1 (representing three concurrent activities A2, A3, and B1), respectively. In the original integrated network, A1 is linked to A2, A3, and B1, respectively. Following transforming, only one link exists between A1 and IE1, and other two links are not visible in the main network (that is, they are hidden inside the subnet of IE1). Table 4 displays the data on duration, predecessors, successors, ES, LS, EF, and LF for each activity and IE for the CI-based schedule. Notably, the duration of each IE is determined by the longest subnet path. For example, the longest path for IE4 (which comprises C4, D1, and D2) is D1→D2. Therefore, the duration of IE4 is 27 days, which is the sum of the 15 days of D1 and the 12 days of D2. Also, the duration of IE2 is 17 days (=7+10) which is sum of the durations of its two critical activities (that is, A6 and A7).

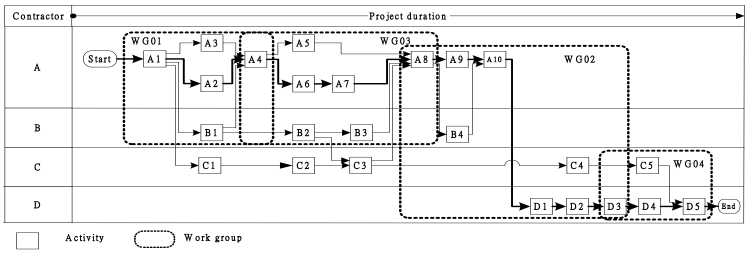

Figure 2. Originally integrated schedule network for the example project

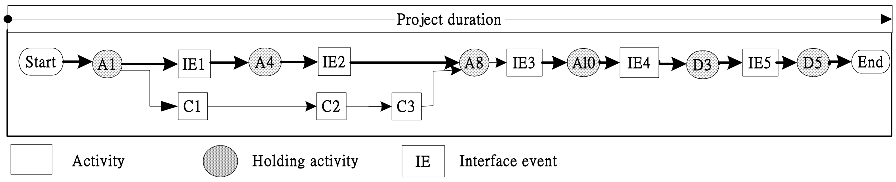

Figure 3. Generated CI-based schedule network for the example project

4.2 *Comparion of CI-based and CPM-based schedules*

The generated CI-based schedule is compared with the original CPM-based schedule in several aspects to indicate the significance of the proposed model. The comparisons are summarized in Table 5 and illustrated as follows.

- Activities. Figure 3 demonstrates that the original 24 activities are reduced to just 14, including five IEs and nine other activities. Among these nine activities, six activities (i.e., A1, A4, A8, A10, D3, and D5) are characterized as either FH or PH activities, and the others (i.e., C1, C2, and C3) are not assigned any special significance in the area of interface management. Also, the number of critical activities is reduced from 13 to 11.
- Links and paths. The number of links is decreased from 31 to 14. Especially, the original 20 network paths are reduced to just two paths existing in the CI-based schedule.
- Project duration. Since the proposed model uses the same basic CPM network calculations, the project durations are the same for both schedules, each lasting 97 days.

5. CONCLUSIONS

This work presents a new scheduling model that integrates both schedule and construction interface management for building construction. The modeling method (that is, establishing work groups, identifying holding activities, mapping interface events, and transforming the schedule) increase schedule readability and hence schedule control effectiveness. Such a readable schedule also provides timing information for resolving interface problems.

Table 2. Network data of the integrated CPM-based schedule for the example project

Act	Dur.	Predecessor	Successor	ES	LS	EF	LF
A1	2	-	A2, A3, B1, C1	0	0	2	2
A2	6	A1	A4	2	2	8	8
A3	5	A1	A4	2	3	7	8
A4	3	A2, A3, B1	A5, A6	8	8	11	11
A5	15	A4	A8	11	13	26	28
A6	7	A4	A7	11	11	18	18
A7	10	A6	A8	18	18	28	28
A8	4	A5, A7, B3, C3	A9, B4	28	28	32	32
A9	5	A8	A10	32	32	37	37
A10	6	A9, B4	D1	37	37	43	43
B1	4	A1	B2	2	11	6	15
B2	7	B1	B3	6	15	13	22
B3	6	B2	A8	13	22	19	28
B4	4	A8	A10	32	33	36	37
C1	3	A1	C2	2	14	5	17
C2	6	C1	C3	5	17	11	23
C3	5	C2	A8, C4	11	23	16	28
C4	2	C3	C5	16	88	18	90
C5	5	C4, D3	D5	80	90	85	95
D1	15	A10	D2	43	43	58	58
D2	12	D1	D3	58	58	70	70
D3	10	D2	D4, C5	70	70	80	80
D4	15	D3	D5	80	80	95	95
D5	2	D4, C5	-	95	95	97	97

ES: early start, LS: late start, EF: early finish, LF: late finish.

Table 3. WGs, IEs, for the example project

Work group	FHa	PH	IE	In-between activities of IE
WG01	A1	A4	IE1	A2, A3, B1
WG03	A4	A8	IE2	A5, A6, A7, B2, B3
WG02	A8	A10	IE3	A9, B4
WG02	A10	D3	IE4	C4, D1, D2
WG04	D3	D5	IE5	C5, D4

FH: front holding activity, PH: post holding, activity

Table 4. Data of CI-based schedule

Activity	Duration	Predecessor	Successor	ES	LS	EF	LF
A1	2	---	IE1, C1	0	0	2	2
IE1	6	A1	A4	2	2	8	8
A4	3	IE1	IE2	8	8	11	11
IE2	17	A4	A8	11	11	28	28
A8	4	IE2, C3	IE3	28	28	32	32
IE3	5	A8	A10	32	32	37	37
A10	6	IE3	IE4	37	37	43	43
IE4	27	A10	D3	43	43	70	70
D3	10	IE4	IE5	70	70	80	80
IE5	15	D3	D5	80	80	95	95
C1	3	A1	C2	2	14	5	17
C2	6	C1	C3	5	17	11	23
C3	5	IE2, C2	A8	11	23	16	28
D5	2	IE5	---	95	95	97	97

Table 5. Comparison of CI and CPM-based schedules

Network	No. of activities	No. of critical activities	No. of links	No. of paths	Project duration
CPM-based	24	13	31	20	97 days
CI-based	14	11	14	2	97 days

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