Network Creation and Development for Repetitive-Unit Projects

Kyoo Jin Yi, M.ASCE[1]; Hyun-Soo Lee, M.ASCE[2]; and Yoon Ki Choi, M.ASCE[3]

Abstract: Network scheduling is typically performed in three phases—network creation, analysis, and development. Although the critical path method (CPM) constitutes a well-established logic in network analysis, human intuition and experience are required for the creation and development of the network. Because of this, a variety of alternative CPM networks can be created in scheduling the same project. The use of the most desirable network can lead to a considerable reduction in the duration of the projects. This can be achieved by accurately identifying activities and linking them in an appropriate manner. Many researchers insisted that network scheduling lacks efficiency in scheduling repetitive-unit projects. Because of this, many scheduling methods have been developed to model such types of projects. However, most are not network based and require a large amount of input data, although most leading scheduling software remains network based and field engineers desire networklike forms of the schedule. In an effort to overcome this limitation, this paper presents a procedure for creating and developing networks for repetitive-unit projects. This network-based model incorporates a two-dimensional arrangement of activities, resource-space coordinates, for ease in creating a network and optimizes the activity linkage, thus resulting in the most desirable results. The model is applied to a typical repetitive-unit project to illustrate the use and capabilities of the model. The model can serve as an aid for inexperienced schedulers in creating a network as well as its optimization. An experienced scheduler can also check the desirability of his or her own created network via the use of this model.

DOI: 10.1061/(ASCE)0733-9364(2002)128:3(257)

CE Database keywords: Networks; Scheduling; Construction industry; Project management.

Introduction

In construction projects, the process of planning, scheduling, and control is, typically, accomplished using the critical path method (CPM) (Mattila and Duley 1998). One of the reasons why CPM is still the most popular and practical scheduling method is because it permits both manual practice and computerized applications, in spite of its weakness in terms of modeling repetitive activities. CPM uses a network diagram, which shows the sequence of work, interdependencies, and interrelationships among project activities.

A typical network scheduling process is performed in three phases—network creation, analysis, and development. In the network creation phase, all activities are defined, along with their logical relationships. To determine when each activity is scheduled to start and finish, all activities and their logical relationships must be defined in advance. Calendar dates are then assigned through network analysis. CPM employs a network analysis method, involving forward and backward pass computation, which logically defines the critical path and performs scheduling to define the scheduled dates of a project and its activities. In the network development phase, the network is redesigned and rearranged in order to obtain the most desirable result.

Although CPM provides a well-established logic in the network analysis phase, creating and developing a network requires intuition and experience. One of the reasons for this is that a construction project is a continuous process rather than an assemblage of discrete events. This continuous process must be converted to a set of discrete events in order to successfully construct a network diagram. Since a variety of methods exist for this conversion, each scheduler usually defines the activities in different styles. As a result, several alternative sets of activities can be generated for the same project.

In the case of repetitive-unit projects, however, it is possible to standardize network creation and development because of the repetitiveness of the crews and space sections. A number of attempts have been made to represent spatial aspects in the modeling construction process, especially for the case of repetitive-unit projects that contain several repetitive units, such as floors in multistory buildings and units in housing developments.

The line of balance (O'Brien 1969), planning construction of repetitive building units (Carr and Meyer 1974), vertical production method (O'Brien 1975), and construction planning technique (Selinger 1980) represent pioneering models, developed prior to the advanced computer techniques currently in use. The time space scheduling method (Stradal and Cacha 1982) incorporated three-dimensional concepts, including time, activity, and space, in a simple two-dimensional chart that displays both the relation of the activities and the space where they take place at a given time. Space-constrained resource-constrained scheduling (Thabet 1992) represents another approach that considers not only horizontal

[1]Assistant Professor, Dept. of Safety Engineering, Hankyong National Univ., Ansung, Kyonggi-do, Korea.

[2]Associate Professor, Dept. of Architecture, Seoul National Univ., Seoul, Korea.

[3]Senior Rect., Dept. of Architectural Engineering, Soongsil Univ., Seoul, Korea.

Note. Discussion open until November 1, 2002. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on March 24, 2000; approved on August 10, 2001. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 128, No. 3, June 1, 2002. ©ASCE, ISSN 0733-9364/2002/3-257–264/$8.00+$.50 per page.

J. Constr. Eng. Manage., 2002, 128(3): 257-264

and vertical logic in scheduling, but space demand and availability as well. Thabet and Beliveau (1997) developed a knowledge-based system for scheduling repetitive-unit projects. Harris et al. (1998) integrated these methods into one generalized model, insisting that each of the above methods was essentially the same, in that they schedule the work in the project by plotting the progress of repetitive activities against time. Harmelink and Rowings (1998) developed the linear scheduling model in order to control the activity path. Tommelein et al. referred to the specialty trades, which work in a continuous and repetitive sequence and move from one floor to another in building construction projects as parades of trades (Tommelein et al. 1999).

Each of these models has its own merits in interpreting space-resource relationships. Many, which concentrate on applying line of balance techniques, are not network-based models, and attempt to overcome the disadvantages of CPM. However, CPM is still the most familiar scheduling method, and continues to serve as the basis for leading computerized tools. Some models require large amounts of input data, which presents practical difficulties for the manual application of the models. Since construction sites are diverse and the working conditions are harsh, available information is often insufficient and the process of gathering sufficient data on tools is not an easy task, especially in the case of developing countries.

The purpose of this study is to provide a network-based procedure for creating and developing a network. This network creation procedure includes the method of generating activities for repetitive-unit projects and then determining the shortest logic from the possible alternatives. Unlike the aforementioned models, the method presented in this paper is compatible with CPM and can be used manually. The procedure arranges the network in resource-space coordinates, which have been used in the past by many researchers, for the easy creation and analysis of the network. This method is primarily designed for manual applications, but schedulers can automate the process with spreadsheet programs.

Basic Concepts

It is convenient for planners if the activities for a project are defined and arranged using the same definite criteria. The activities, basic elements of network scheduling, can be generated by dividing the continuous process of construction into a set of discrete elements. A well-defined activity is an activity that is as discrete as possible without omitting any part of the construction process. An activity that overlaps with another activity is inappropriate and can be confusing. One possible solution for this is defining and arranging activities according to several discrete elements of a construction project. Among the elements of a construction project, several resources, such as work crews, can be regarded as discrete. In a multiunit project, the spaces, such as units or sections, can also be considered to be discrete.

Even after the activities have been defined, there still remain many chances for choice in terms of establishing the logical relationships among the activities. In other words, it is possible to draw a different logic for the same set of activities. The project completion time can be changed, not only by crashing activities on the critical path, but also by changing the logical relationships of the activities. For this reason, establishing proper logical relationships is important in planning as well as defining activities and analyzing the network.

Alternatives of Work Progress Patterns

Several alternatives are available for scheduling a repetitive-unit construction project. Fig. 1 contains an example, which shows three possible alternatives for work progress patterns for a simple project. Stradal and Cacha (1982) classified such work progress patterns into three basic categories—successive proceeding, flow line proceeding, and simultaneous proceeding.

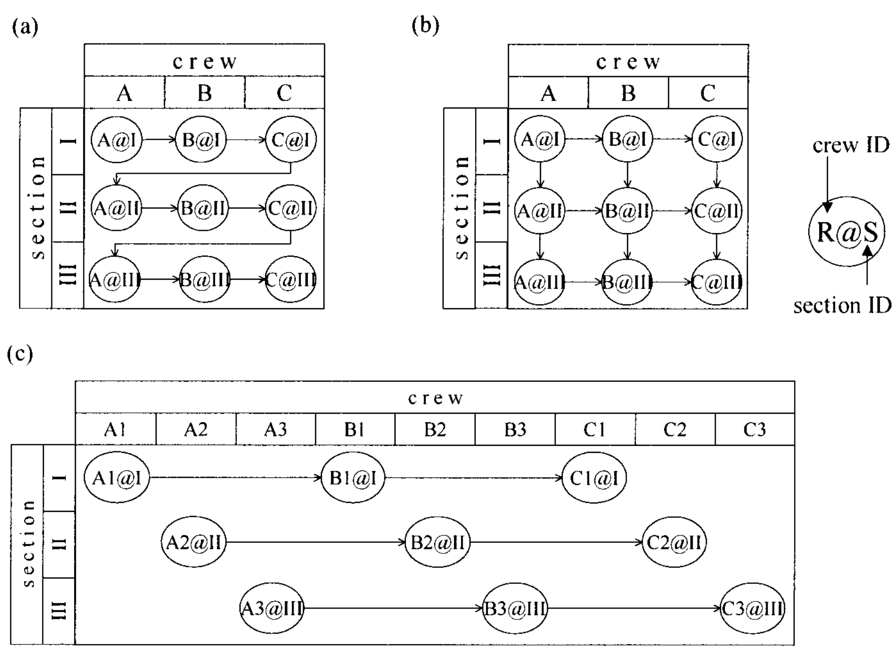

Fig. 1. Alternatives of work progress patterns: (a) successive proceeding; (b) flow line proceeding; (c) simultaneous proceeding

J. Constr. Eng. Manage., 2002, 128(3): 257-264

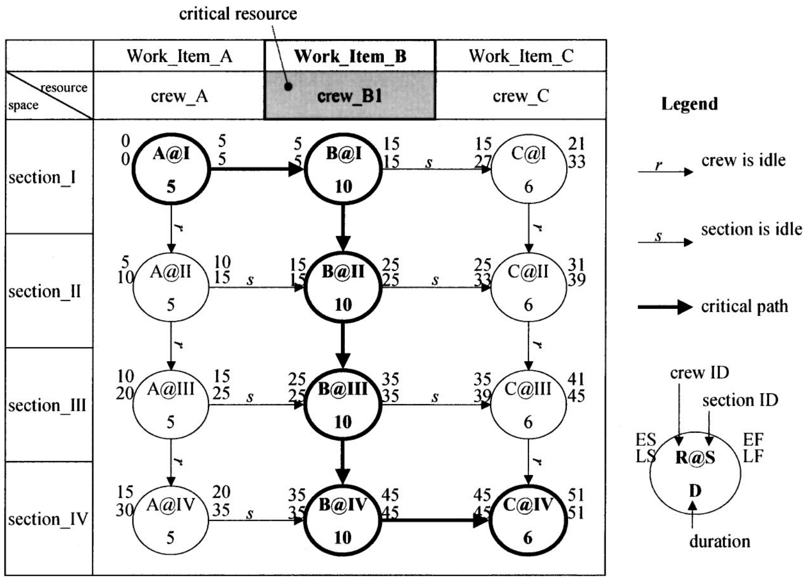

Fig. 2. Critical path method network 1—single crew for work item B

Activity Arrangement

Flow line proceeding is adopted by many schedulers as an alternative to enhancing efficiency in repetitive-unit projects. In flow line proceeding, each resource consecutively moves from one place to another and the next resource follows the predecessor, as shown in Fig. 1. In such projects, activities can be represented in the form of a resource-space coordinate, with resources on the horizontal axis and space on the vertical axis. Each activity, in the case of repetitive-unit projects, can be marked as work-item(resource@space). In Fig. 1, B@II indicates that crew B is scheduled to perform an activity at section II. For instance, when a carpenter is scheduled to perform woodwork in the living room on the third floor, one can mark such an activity as woodwork(carpenter@living_room.3rd_floor).

Resource Path and Space Path

Fig. 2 shows a simplified network schedule in which three independent crews, A, B, and C, are scheduled to perform activities in four sections of space, I, II, III, and IV. The work durations for the crews A, B, and C are assumed as 5, 10, and 6 days, respectively. The horizontal paths indicate the crews for each section, and the vertical paths indicate the sections for each crew. This research specifies the horizontal path as a "space path," and the vertical path as a "resource path." For example, the path A@I→B@I →C@I represents the path for section I, and the path B@I →B@II→B@III→B@IV represents that of crew B. In Fig. 2, crew B follows crew A on the path for section I, which means that the task for crew B should be started at section I after crew A is finished at section I. When crew B follows crew A on the path for

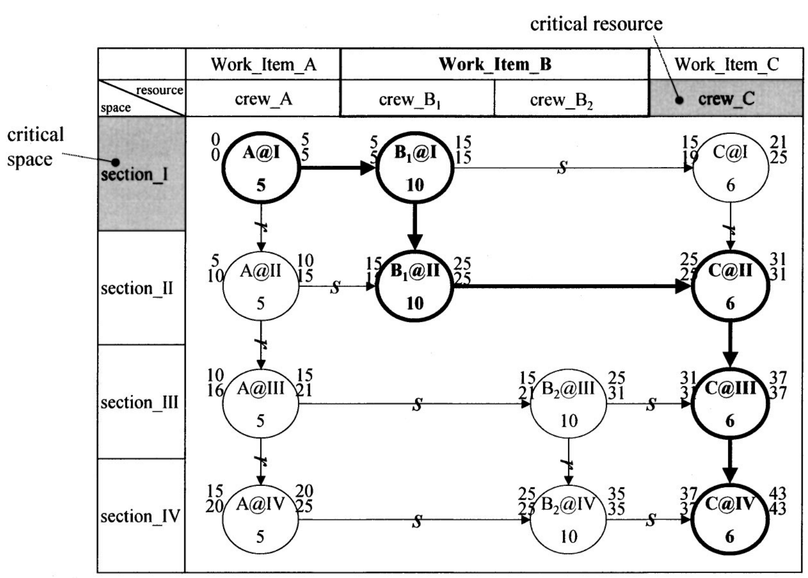

Fig. 3. Critical path method network 2—double crews for work item B

J. Constr. Eng. Manage., 2002, 128(3): 257-264

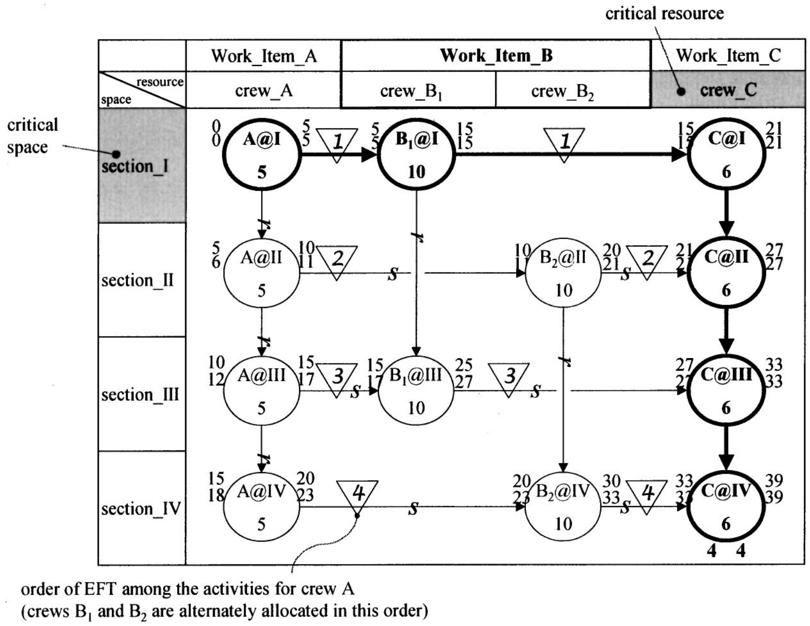

Fig. 4. Critical path method network 3—double crews for work item B, reallocated

section I in a network, this study designates crew A as the preceding resource for crew B on the path for section I, and crew B as the succeeding resource for crew A on the path for section I. Likewise, when section II succeeds section I on the path for crew A, this research designates section I as the preceding space for section II on the path for crew A, and section II as the succeeding space for section I on the path for crew A.

Idle Resources and Idle Spaces

In Fig. 2, the path for crew B is a part of the critical path, yet crews A and C have slack time, except for only one activity for each crew. For instance, crew C, after finishing its work at section III, cannot proceed to section IV for four days, since the resource predecessor, crew B, is still working at section IV. Crew C then must remain ''idle'' for four days. In the same way, ''idle'' space is possible where there is no work for a period of time. For instance, there is no activity at section II for five days after crew A finishes, since crew B has not yet finished its work at section I. As a result, section II remains idle for a five-day period. Such idle resources and idle spaces are the major causes of efficiency loss, which is undesirable for the continuity of the work. Reducing such slack is one of the goals of project scheduling.

Critical Resource Path and Critical Space Path

If there is no slack on a resource path, the path can be called ''critical.'' Similarly, a space path can be called critical if there is no slack on that path. In Fig. 2, the path for crew B is critical, yet there is no critical space path.

Resources for Same Work Item

One way to expedite the duration of a project is for more than one crew or piece of equipment to simultaneously perform the same work item at different places. In Fig. 3, crews B_1 and B_2 share the work item B, such that crew B_1 can work at sections I and II and crew B_2 can work at sections III and IV. The crews B_1 and B_2 represent the resources for the same work item.

Schedule Compression: Minimizing Idle Resources and Idle Spaces

In typical schedule compression, the duration of a project approaches the minimum by consecutively crashing the activities on

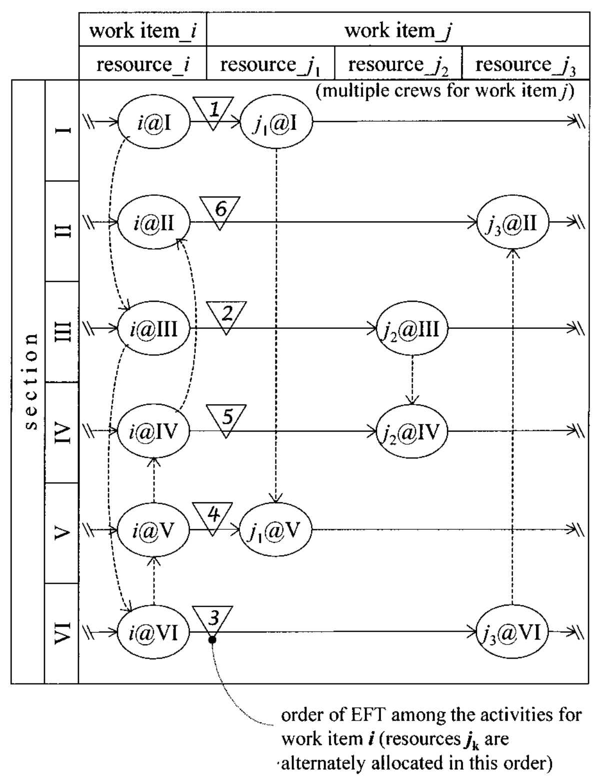

Fig. 5. Activity linking procedure

J. Constr. Eng. Manage., 2002, 128(3): 257-264

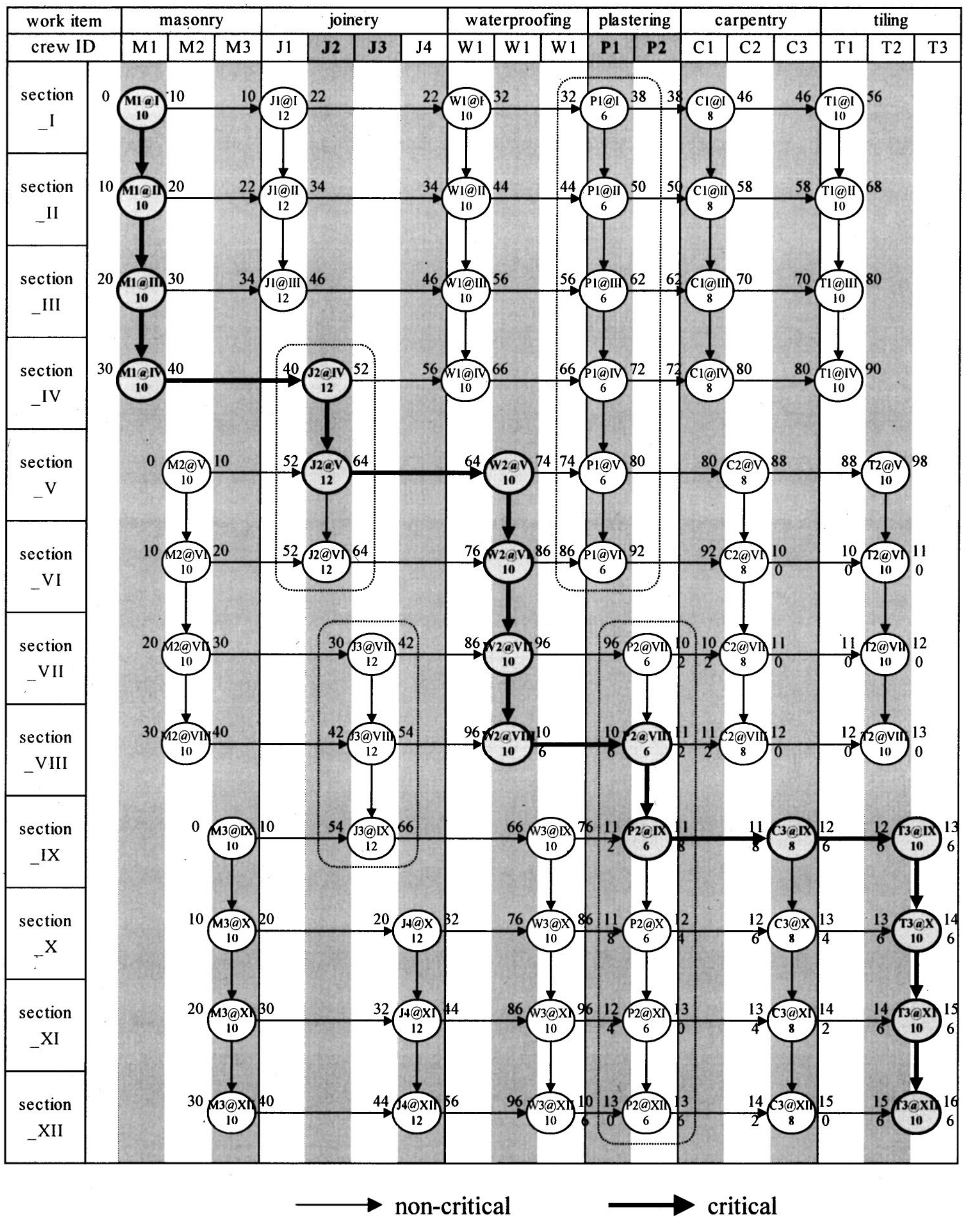

Fig. 6. Example (before adjustment)

the critical path until no activities that can be crashed remain. Crash can be accomplished by using a larger crew, overtime, extra shifts, or any combination of the three (O'Brien 1993). In this example, increasing the number of workers in the crew will be considered for compressing the critical resource path. Figs. 3 and 4 show an example of schedule compression steps. In Fig. 3, using two crews, the path for crew B is also divided into two separate paths. Sections I and II are assigned to crew B_1; sections III and IV are assigned to crew B_2. Crews B_1 and B_2 are independent crews, but they perform the same work item. The entire duration is reduced from 51 to 43 days, yet the network in Fig. 3 still appears to be undesirable, since room exists for compression.

If crew B_1 takes sections I and III and crew B_2 takes sections II and IV, as shown in Fig. 4, four more days can be saved. In this case, the duration of the network can be reduced to 39 days, which makes section I and crew C critical. Further compression can be achieved by crashing the activities on the path for crew C or overlapping the activities on the path for sections I and II. In this example, the latter case is considered.

Optimizing Activity Arrangement

The schedule compression shown in Figs. 2–4 represents only a simple abstract—the arrangement of which can easily be optimized by intuition. In a real situation, in which more complicated sets of activities are involved, a systematic procedure for optimizing the activity arrangement will be required. This research provides a method for optimizing the activity, as illustrated in Fig. 5.

In the case of Fig. 5, one crew (resource i) for work item i and three crews (resources j_1, j_2, and j_3) for work item j (i precedes j) perform activities in six sections of space (sections I, II, . . . , VI). In Fig. 5, the work item i is assumed to precede work item j; thus, resources j_1, j_2, and j_3 follow the resource i. On the other

J. Constr. Eng. Manage., 2002, 128(3): 257-264

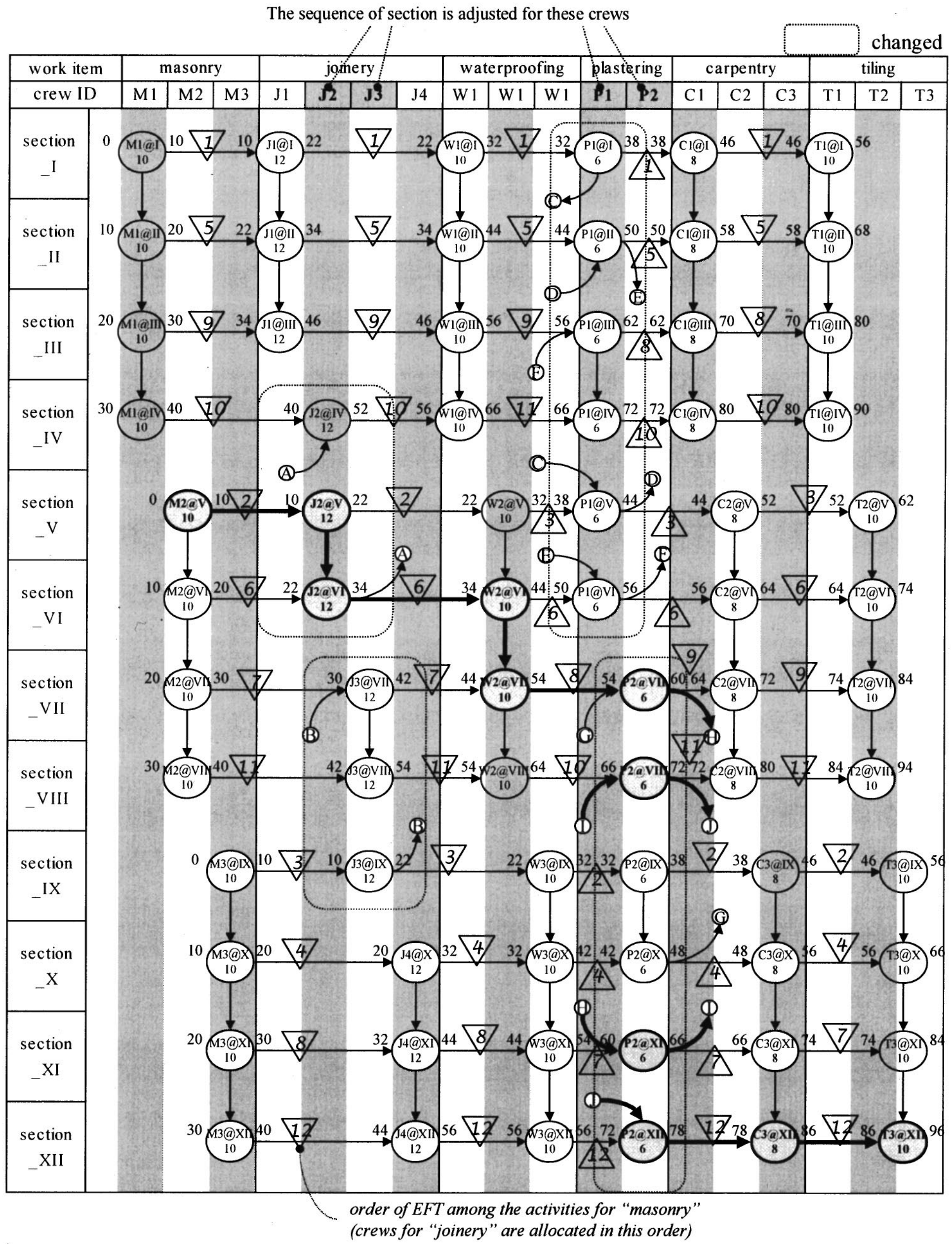

Fig. 7. Example (after adjustment)

hand, it is assumed that there is no precedence relationship among the sections, so the activities $i@\mathrm{I}$, $i@\mathrm{II},\ldots,i@\mathrm{VI}$ are temporarily linked in order of the section numbers. The network optimization for Fig. 5 can be performed in the following steps:

1. Adjusting the sequence of activities on the path for a resource belonging to a work item *i*. To minimize the idle time of the resources, the temporary linkages on the resource path must be adjusted. This can be achieved by linking the activities on the resource path according to the sequence of earliest finish time (EFT) of each activity. The steps involved in this adjustment can be summarized as follows:
   • Unlink the temporary linkage among the activities on the path for the resource;
   • Calculate the EFT of each activity on the path for that resource;
   • Relink the activities according to the EFT sequence, starting from the activity corresponding to the earliest EFT. The next earliest one follows it, and then the third earliest, and so forth;
   • Recalculate the EFT; and
   • Follow the above steps for the remaining resources, if any, for the work item *i*.
2. Adjust the successors in work item *j*. After adjusting the sequence of sections for a resource, its successive resources are allocated to each section such that the idle times of the resources are minimized. In Fig. 5, work item *i* is followed by work item *j*. The problem is how to minimize the idle times of the three resources, j_1, j_2, and j_3, in allocating to the six sections, the process of which can be summarized as follows:
   • Allocate resources belonging to work item *j* according to the sequence of EFT of the activities in work item *i* (the numbers inside the reversed triangles in Fig. 5 indicate the sequence of EFT); and

J. Constr. Eng. Manage., 2002, 128(3): 257-264

Table 1. Work Items for Example Projects

Order	Work item	Duration	Number of crews available
1	Masonry	10	3
2	Joinery	12	4
3	Waterproofing	10	3
4	Plastering	6	2
5	Carpentry	8	3
6	Tiling	10	3

Table 2. Sections for Example Projects

Section_ID	Building ID number	Floors
I	1	1–6
II	2	1–6
III	3	1–6
IV	4	1–6
V	1	7–12
VI	2	7–12
VII	3	7–12
VIII	4	7–12
IX	1	13–18
X	2	13–18
XI	3	13–18
XII	4	13–18

Note: ID = identification.

- If there is more than one resource associated with work item *j*, allocate the resources alternately according to the sequence of the EFT of the activities in work item *i*. For instance, if crews j_1, j_2, and j_3 belong to the work item *j*, allocate j_1 to the earliest one, j_2 to the next earliest, j_3 to the third earliest, and then j_1 again to the fourth earliest.

3. Until no succeeding work items remain for the work item *j*, let work item *j* be work item *i* and let the succeeding work item be work item *j*, and return to step 1.

Example

An example of the creation and development of a network is shown in Figs. 6 and 7. Tables 1–3 show the abstracts for the crew allocation plan for a typical apartment complex in the Seoul area. This project is for the simultaneous construction of four 18-story apartment buildings. In such construction sites, with limited resources available, one possible solution is to prepare layout plans, in which the entire site is divided into several sections. In this case, the site can be divided into 12 sections for finish work, with six floors per section, as shown in Table 2. Table 1 shows the duration for each work item and the number of crews available. The available crews are allocated to each section, as shown in Table 3.

Fig. 6 shows an abstract network for finish work. The network in Fig. 6 appears correct in terms of network logic, but it is no better than one of the worst alternatives. The 166 days of duration of the network in Fig. 6 contain too much slack, and need to be adjusted for expedition. How can an inexperienced scheduler check such a network and adjust it to achieve a desirable alternative? The linkages of the activities encircled by a dotted line are relinked according to the network development procedure, and Fig. 7 shows one of the alternatives for the adjustment. One important assumption for this calculation is that more than one work item cannot be performed simultaneously at the same place. The calculation process for this adjustment can be performed using the following steps:

1. Calculate the EFT of the activities that belong to ''masonry.''
2. Number these activities in order of EFT, from earliest to latest. Activities that have the same EFT can be numbered at the scheduler's convenience. For instance, since the activities M1@I, M2@V, and M3@IX have the same EFT, they are numbered 1, 2, and 3, respectively, as indicated in the reversed triangles in Fig. 7. Likewise, the next earliest, M3@X, M1@II, and M2@VI, are numbered 4, 5, and 6. Other activities are numbered in the same manner.
3. Link the activities belonging to ''joinery'' to the activities of ''masonry.'' The resources of joinery, J1, J2, J3, and J4, are alternately linked to the activities belonging to masonry in the order of the numbers given in step 2. For instance, J1, J2, J3, and J4 are linked to M1@I, M2@V, M3@IX, and M3@X, respectively. The remaining activities are linked in the same manner.
4. Link the activities along the resource path. The activities being performed by the same resource are linked to one another in the order of the EFT of their predecessors in masonry. In the case of J2, for instance, J2's three predecessors, M2@IV, M2@dV, and M2@VI, have EFT values of 10, 20, and 40, respectively; therefore, J2's activities are linked as j2@V→j2@VI→j2@IV.

Table 3. Allocating Work Crews to Sections

Section_ID	Masonry	Joinery	Waterproofing	Plastering	Carpentry	Tiling
I	M1	J1	W1	P1	C1	T1
II	M1	J1	W1	P1	C1	T1
III	M1	J1	W1	P1	C1	T1
IV	M1	J2	W1	P1	C1	T1
V	M2	J2	W2	P1	C2	T2
VI	M2	J2	W2	P1	C2	T2
VII	M2	J3	W2	P2	C2	T2
VIII	M2	J3	W2	P2	C2	T2
IX	M3	J3	W3	P2	C3	T3
X	M3	J4	W3	P2	C3	T3
XI	M3	J4	W3	P2	C3	T3
XII	M3	J4	W3	P2	C3	T3

Note: ID = identification.

J. Constr. Eng. Manage., 2002, 128(3): 257-264

5. Follow the above steps for joinery and ''waterproofing'' in similar ways. This time, joinery is the predecessor and waterproofing is the successor. The activities of the remaining work items follow the above steps.

The 166 days for the original network can be reduced to 96 days, thus saving as many as 70 days (up to 42% of the original). This result shows that the duration can vary considerably in network scheduling by a simple adjustment in the links among the activities that are associated with the same work item. It also shows that, in schedule compression, the scheduler must carefully check the linkages of activities before crashing the critical path, especially in the case of repetitive activities.

Conclusion

With modern computer technology, it is a simple and easy task to check network logic and calculate duration, once a complete network schedule is provided. However, human intuition is still required in creating a draft network and in developing it into a more efficient one, a network of desirable duration.

In repetitive-unit projects, a number of alternatives exist, because of the repetitiveness of the crews and space sections. When several crews perform the same work item at different sections, the scheduler should consider not only the sequence of work items, but also the sequence of sections and crews involved in each work item.

This paper presents a method for network construction and development for use in repetitive-unit projects. By applying the network development procedure to a typical repetitive-unit project, the reallocation of the crews and sections compressed the network considerably, without any change in the sequence of work items. An example network was constructed by arranging the activities in the crew and section coordinates, as many researchers have used in the past. The network development procedure was then applied, in order to enhance the efficiency of that network. By relocating the crews and adjusting the sequence of sections for each work item, the network could be redesigned, thus minimizing the idle time of the crews and the sections. This network construction and development method can aid inexperienced schedulers in creating a network for repetitive-unit projects. It can also help the experienced schedulers to examine the efficiency of their own created network.

Acknowledgment

This work was supported by a Korea Research Foundation grant (KRF-2000-003-E00645).

References

Carr, R. I., and Meyer, W. L. (1974). ''Planning construction of repetitive building units.'' *J. Constr. Div., Am. Soc. Civ. Eng.*, 100(3), 403–412.

Harmelink, D. J., and Rowings, J. E. (1998). ''Linear scheduling model: Development of controlling activity path.'' *J. Constr. Eng. Manage.*, 124(4), 263–268.

Harris, R. B., et al. (1998). ''Scheduling projects with repeating activities.'' *J. Constr. Eng. Manage.*, 124(4), 269–278.

Mattila, K. G., and Dulcy, M. A. (1998). ''Resource leveling of linear schedules using integer linear programming.'' *J. Constr. Eng. Manage.*, 124(3), 232–244.

O'Brien, J. J. (1969). *Scheduling handbook*, McGraw-Hill, New York.

O'Brien, J. J. (1975). ''VPM scheduling for high-rise buildings.'' *J. Constr. Div., Am. Soc. Civ. Eng.*, 101(4), 895–905.

O'Brien, J. J. (1993). *CPM in construction management*, 4th Ed., McGraw-Hill, New York.

Selinger, S. (1980). ''Construction planning for linear projects.'' *J. Constr. Div., Am. Soc. Civ. Eng.*, 106(2), 195–205.

Stradal, O., and Cacha, J. (1982). ''Time space scheduling method.'' *J. Constr. Div., Am. Soc. Civ. Eng.*, 108(3), 445–457.

Thabet, W. Y. (1992). ''A space-constrained resource-constrained scheduling system for multi-story buildings.'' PhD dissertation, Virginia Tech, Blacksburg, Va.

Thabet, W. Y., and Beliveau, Y. J. (1997). ''SCaRC: Space-constrained resource-constrained scheduling system.'' *J. Comput. Civ. Eng.*, 11(1), 48–59.

Tommelein, I. D., Riley, D. R., and Howell, G. A. (1999). ''Parade game: Impact of work flow variability on trade performance.'' *J. Constr. Eng. Manage.*, 125(5), 304–310.

J. Constr. Eng. Manage., 2002, 128(3): 257-264