Incorporation of Alternatives and Importance Levels in Scheduling Complex Construction Programs

Yuhong Wang, P.E.[1]; Yun Le[2]; and Jiukun Dai[3]

Abstract: A complex construction program usually consists of a group of interrelated projects with different levels of importance and degrees of certainty. Currently, time management of a construction program uses the same techniques as those for a single project, and the most commonly used technique is the critical path method (CPM). However, the CPM method lacks flexibility in handling uncertainties and options, a desirable feature in managing complex programs. This paper proposes a new scheduling method that is drawn from the authors' experiences of managing a large-scale construction program—the Shanghai Expo facility construction. The new method is developed on the basis of the traditional CPM method but is able to incorporate options and importance levels into the program schedule. The theoretical basis and calculation method of this new scheduling technique are discussed in the context of managing the Shanghai Expo facility construction program. This paper contributes to the body of knowledge in construction management by developing a new scheduling technique with proven applications. **DOI: 10.1061/(ASCE)ME.1943-5479.0000349.** © *2014 American Society of Civil Engineers.*

Author keywords: Project management; Scheduling; Critical path method; Construction costs; Control.

Introduction

Although the terms *project* and *program* are sometimes used interchangeably (e.g., Barrie and Paulson 1992) in the context of construction management, they are now often treated as different concepts. According to the Project Management Institute (PMI), a program is "a group of related projects managed in a coordinated manner to obtain benefits and control not available from managing them individually" (PMI 2008). Similar definitions of *program* have been provided in other sources (e.g., Artto et al. 2009; Sanghera 2008; Wagner 2009). In construction, it is not uncommon for a group of projects to be implemented simultaneously, and the removal of one or more projects from the group may not seriously affect the overall program goals. Hence, it is more appropriate to refer to the group of projects as a program instead of a single, large project. Examples of construction programs include the Measure R in the United States (LA Metropolitan Transportation Authority 2012) and the 2010 Shanghai Expo facility construction program in China. The former consists of dozens of transit and highway projects with estimated costs totaling $40 billion, while the latter consists of more than 400 buildings in addition to many urban infrastructures.

Although programs are commonly encountered in construction, research on program management is relatively recent and scarce, compared with the large amount of research on project management. Moreover, the limited literature on program management mainly focuses on conceptual, organizational, and behavioral issues. Research on fundamental and practical methodologies for effective program management is lacking. As a result, program management today still heavily relies on the traditional techniques for project management.

A key component in project and program management is time management. A variety of traditional techniques have been used to develop project schedules, including the Gantt chart by Henry L. Gantt (Weber 2004), critical path method (CPM) (Kelly 1961), program (it actually means project) evaluation and review technique (PERT) (Malcolm et al. 1959), and linear scheduling method (e.g., Johnston 1981), etc. Of these traditional techniques, PERT is the only one that enables a scheduler to address uncertainty in a project schedule by associating activity durations with probability distributions. However, using PERT to handle uncertainty has been criticized for the following reasons: (1) historical data to support the development of the probability distribution functions of the activity durations is usually unavailable (Herroelen and Leus 2005), and (2) it does not explicitly address the sources of uncertainty (Khodakarami et al. 2007). In recent years, several new techniques have been proposed to accommodate uncertainty in project scheduling. One technique that gains popularity is the critical chain scheduling (CCS) method, which incorporates task dependencies, resource availability, and four types of buffers (project, feeding, resource, capacity) into a project schedule (Goldratt 1997). In addition, Herroelen and Leus (2005) summarized five approaches to dealing with uncertainty: reactive scheduling (e.g., Szelke and Kerr 1994; Sabuncuoglu and Bayiz 2000), stochastic scheduling (Demeulemeester and Herroelen 2002), fuzzy scheduling (e.g., Slowinski and Hapke 2000), proactive (robust) scheduling (e.g., Davenport et al. 2001; Mehta and Uzsoy 1999), and sensitivity analysis (e.g., Hall and Posner 2004). However, these five approaches mainly deal with the uncertainties in activity and project durations, not the uncertainties in the network structure that defines the logical relationships among the activities or projects. Consequently, although the estimated activity durations are allowed to vary, the logical relationships among the activities are fixed and governed by the predetermined network structure. In construction

[1]Assitant Professor, Dept. of Civil and Structural Engineering, Hong Kong Polytechnic Univ., Hung Hom, Hong Kong (corresponding author). E-mail: ceyhwang@polyu.edu.hk

[2]Chair and Professor, Dept. of Construction Management and Real Estate, Tongji Univ., Shanghai, China; and General Program Manager for the Shanghai Expo Construction Program, Shanghai Kerui Inc., Shanghai, China

[3]Performance Engineer, FLUOR, 100 Fluor Daniel Dr., C502, Greenville, SC 29607

Note. This manuscript was submitted on April 23, 2014; approved on October 22, 2014; published online on December 3, 2014. Discussion period open until May 3, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Management in Engineering***, © ASCE, ISSN 0742-597X/04014098(10)/$25.00.

literature, the use of different algorithms to optimize construction schedules has been discussed (e.g., Orouji et al. 2014), but the research is mainly based on a presumed project network structure. This is often undesirable for scheduling a construction program in a real situation where the network structure itself is also subject to variations due to the addition, removal, and/or adjustment of project/program components. The rigidity of the network structure limits the potential of the program schedule to provide more insightful and comprehensive information to decision makers and implementers. For example, a program may consist of multiple projects with different levels of importance, dependent on their respective contributions to the overall program goals. When the resource or time becomes insufficient to support all the projects, the program manager may wish to identify and implement some projects or certain components of the projects that are most essential to the program goals and simultaneously maintain a logical sequence. In addition, the program manager may wish to include alternative plans (Plan B) in the program schedule to increase flexibility in program implementation. The existing scheduling methods leave much to be desired in these aspects.

This paper is based on the authors' involvement in and reflection on the management of the facility construction program for the 2010 Shanghai World Expo. The program consists of hundreds of projects and tens of thousands of activities. A hierarchical network scheduling approach was used to manage the program's schedule. In the hierarchical structure, the program schedule was divided into several layers and the degree of detail for the schedule increased from the top layer to the bottom one. At each layer, traditional scheduling techniques such as the Gantt chart and CPM scheduling methods were used. However, the traditional techniques do not provide sufficient flexibility to handle variations in project importance, uncertainties and contingencies for program planning and control, especially at the early stage of program development. This paper proposes a new scheduling technique for programs. The technique makes it possible to evaluate the relative importance of projects within a program and/or the relative importance of activities within a project; it also enables the inclusion of alternatives in the overall program schedule.

Background

CPM is widely used in construction project scheduling. However, there are several limitations on the use of CPM to schedule complex construction programs. These limitations are discussed as follows.

First, CPM does not show the intrinsic importance level of program (project) activities. A program comprises multiple projects and/or subprograms, but not all of them are equally important with respect to their contributions to the overall program goals (e.g., social and financial). Such variations in importance at the project or subprogram level will pass onto the activities, making them vary in importance, too. However, in a CPM schedule, the importance of the activities is based on their floats—the amount of free time that the activities possess without affecting the overall project duration. When resource or time is constrained, priorities will be assigned to activities on the critical path or with the fewer amounts of floats. Therefore, when using CPM for program scheduling, a project, which is the least important in the overall program in terms of its contribution to the essential program functions and goals, may become critical solely because the project's activities have zero float. This makes it difficult for the program manager to identify and track the true priorities in the program.

Secondly, uncertainties and alternatives are difficult to incorporate into a program schedule. The uncertainties may arise from several sources (Herroelen and Leus 2005), including: ambiguous definition on program/project scopes, inaccurate estimate of activity durations, availability of funding or resources, and weather conditions, or other contingencies. The deeper causes of the uncertainties may include ignorance, lack of information or lack of control (Chang 2002). Although different approaches have been proposed to reduce uncertainties, such as the early involvement of contractors in project development (Song et al. 2009), many uncertainties still exist. For example, in the Shanghai Expo construction program, the site was already under construction before the schematic design of the landmark building, the China Pavilion, was started. Some projects remained undecided until the late very stage of program implementation due to funding issues. Such uncertainties during the implementation stage of the program create challenges in planning and scheduling. On the other hand, these uncertainties make it important to add certain flexibility to the program schedule, such as alternative solutions. It is critically important to find a mechanism to incorporate the uncertainties and alternatives into the program schedule.

Thirdly, because of their limitations in handling priorities and alternatives, CPM does not provide sufficient information for sensitivity-based program evaluation and contingency management. In evaluating and planning programs, the decision makers need to define the scopes, weigh the trade-offs between different alternatives, and identify and update the demand for resources and their availability. Thus, there are many *what-if* questions to ask during this process. At the planning stage, it would help decision makers effectively answer the questions above if the program schedule can provide cost and time information with respect to different assumptions and options. At the implementation stage, contingencies may arise in construction, including time delays, significant cost overruns, or funding shortages. The influence of these contingencies on a program may be illustrated in Fig. 1. The planned program, as shown in the left side of Fig. 1, has a group of directly or indirectly connected projects as well as a certain funding level and duration associated with the program. As the program proceeds, time and cost overruns or funding reductions may make it necessary to change the original scope of the program, if the program still needs to be completed within the original budget and time frame. Therefore, the program manager will have to decide which projects or project components should be adjusted, trimmed, or even eliminated. The impacts of such adjustments on a program schedule need to be carefully reviewed.

Proposed Process for Developing Program Schedules

With these issues in mind and the authors' experience of managing the Shanghai Expo construction program, a new technique for

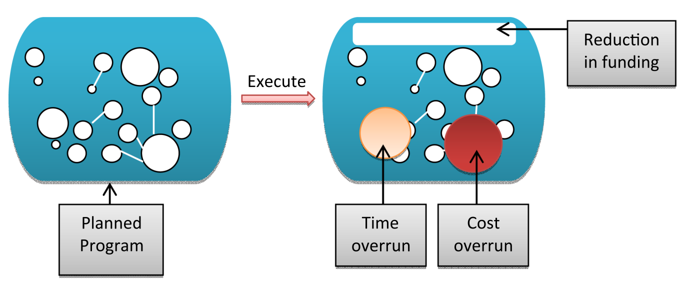

Fig. 1. Effects of funding reduction, time, and cost overruns on program schedule

program scheduling is proposed. The proposed technique consists of the following steps:

1. Definition of the importance levels of projects and their activities;
2. Identification of the logic relationships between the activities;
3. Computation of the program schedule;
4. Analysis and optimization of the program schedule; and
5. Update of the program schedule.

Implementation of these steps requires six propositions that must be satisfied. One of the propositions is presented in Step 1—importance level definition for projects and their activities. The remaining five propositions are presented in Step 3—computation of the program schedule. The steps and propositions are discussed as follows.

Step 1: Definition of the Importance Levels for Projects and Their Activities

Techniques for ranking and prioritizing projects are widely studied in existing literature (e.g., Figueira et al. 2005). Projects can be evaluated based on a single criterion or a set of criteria. An example of the single criterion is the economic return in terms of the net present value, benefit-cost-ratio, rate of return, or others. Examples of multicriteria decision-making (MCDM) methods include goal programming (e.g., Figueira et al. 2005), analytic hierarchy process (e.g., Saaty 2005), and others. Based on the evaluation results, a group of projects, perhaps with different ranking scores, are selected to enter the program. During the project selection stage, the interdependencies between the projects also need to be considered. In spite of the evaluation methods used, each project or subprogram should have implicit or explicit level of importance at the end of the evaluation period. Such information is, however, often lost later on when the program schedule is developed. One objective of this proposed scheduling technique is to retain the project ranking information in the scheduling process.

Proposition 1

The chosen projects and subprograms in a program schedule inherit the levels of importance from the program definition stage, and all the scheduled activities initially have the same level of importance as the main projects or subprograms to which they belong.

The importance of a project or subprogram may be initially designated by a numerical ranking score, which needs to be converted to a discrete importance level to simplify scheduling calculation. The scheduled activities initially inherit the same level of importance from the project, but the importance of the activities may be changed in the subsequent scheduling process, as will be discussed later. The conventional diagrams used in CPM may be revised to indicate the activities' importance levels. Fig. 2 shows two possible ways of representing the importance of an activity. In the figure, a lower number is assumed to represent a higher importance level.

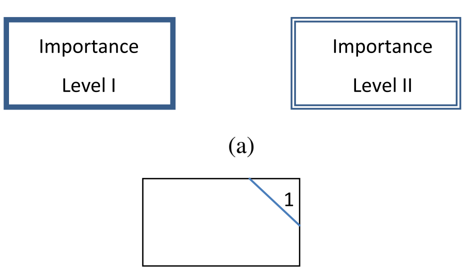

Fig. 2. Representation of activities with different importance levels: (a) use of different line styles to show importance level of an activity; (b) use of a number at the right upper corner of the activity box to show importance level of an activity

Step 2: Identification of Logic Relationships between Activities

All the activities in a program schedule should be connected to other activities. A connection may be established between two activities that belong to a same project or that belong to different projects. However, because most projects in a program are typically implemented independently, extensive connections between the projects are not expected. If there are a large number of interproject connections, the two or multiple projects may be merged into one.

Besides the commonly used deterministic connections between the activities, another type of connection, *optional connection*, is used in the proposed scheduling method. An option represents a project component, a construction method, or an entire project, which can be replaced by its alternative(s) without seriously affecting the program's core objectives. For instance, either a footbridge or an underground tunnel may be a feasible alternative to facilitate traffic flow in a particular area. Although both alternatives can meet the same functional requirements, their effects on project time and cost may be different. The diagram in Fig. 3 illustrates how the *options* or *alternatives* can be represented in a program schedule.

Step 3: Computation of the Program Schedule

The proposed scheduling method integrates alternatives and activities with different levels of importance into a conventional CPM schedule. The calculation method for this new network is demonstrated by an example in Fig. 4. The same conventions for the precedence diagram are adopted in this network, with nodes representing activities and arrows representing logical relationships. To simplify the discussion, the relationships between the activities are assumed to be *finish-to-start*. Unlike the conventional precedence diagram, however, Fig. 4 includes project alternatives and activity importance information that is derived from the previous steps. It is assumed that the program shown in Fig. 4 consists of five projects with three importance levels. Initially, all the activities that belong to a certain project have the same level of importance. In addition, at the project level, Projects 4 and 5 are two exchangeable alternatives that may equally satisfy the key program objectives or functions. At the activity level, Activities G3 and H3 in Project 3 are also exchangeable alternatives. The alternative projects or activities are designated by the circles in Fig. 4. The inclusion of such information affects the CPM calculation method. It is found that, in order to carry out logical calculation, Propositions

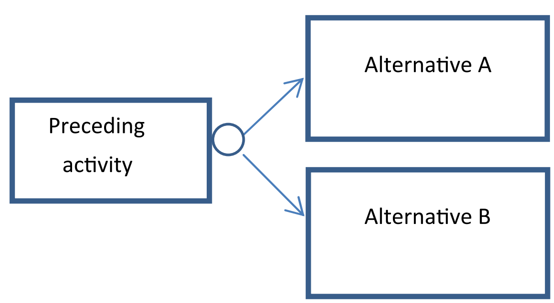

Fig. 3. Graphical representation of alternatives

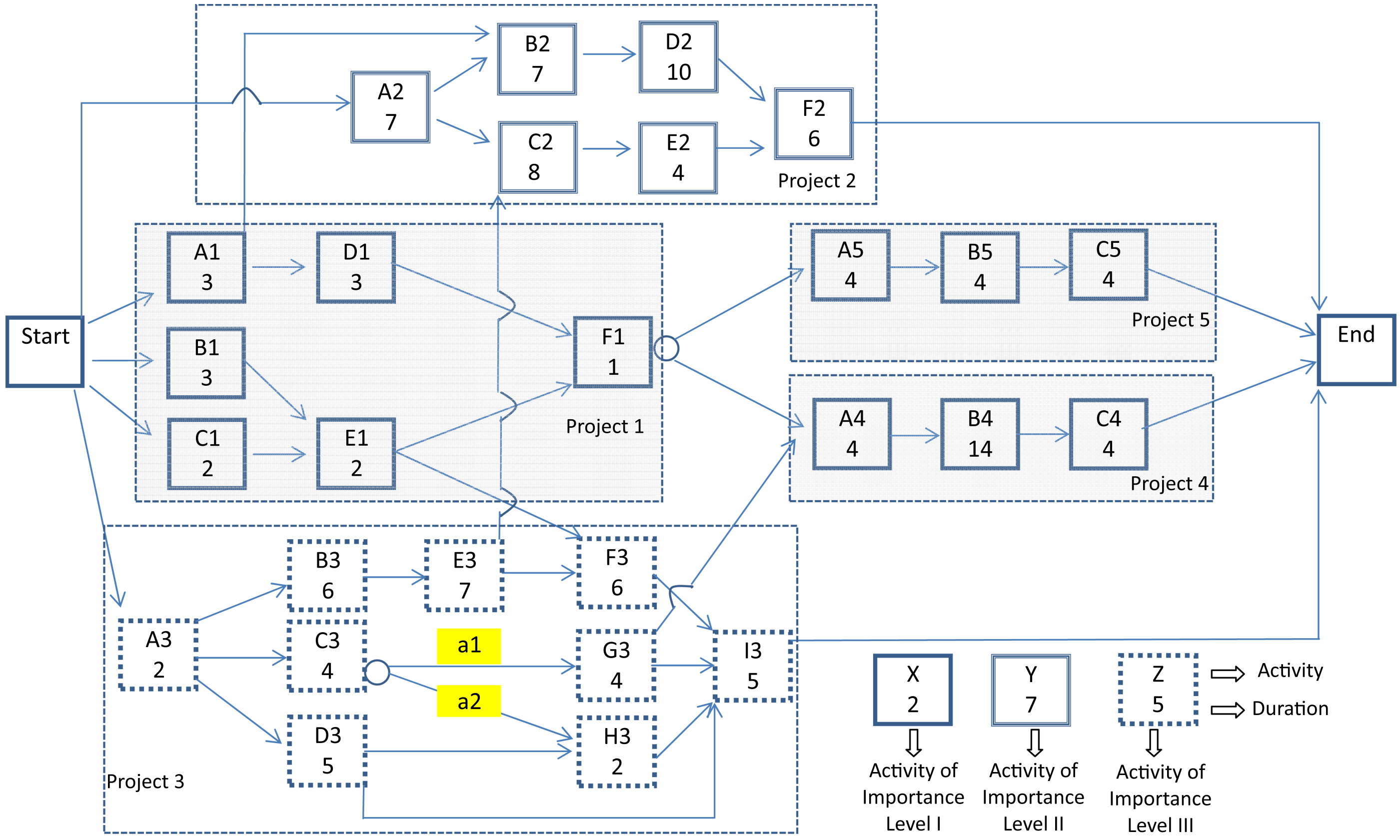

Fig. 4. Example of program schedule

2–6 must be satisfied. Each of the propositions is described as follows.

Proposition 2

A program has a single start activity and a single end activity.

This proposition is to differentiate a program from an ongoing, routine operation. It is also an important assumption to apply the CPM scheduling techniques to program scheduling. If the program has no end activity, it is impossible to carry out backward calculation.

Proposition 3

An activity may possess multiple levels of importance derived from connections with other activities. Except for the last activity, the importance level of an activity's preceding activity (or activities) should be greater than or equal to the importance level of this activity.

All activities within the same project initially have the same level of importance according to Proposition 1; therefore, Proposition 3 is mainly used to govern activities with interproject relationships. For two activities that have a *finish-to-start* relationship but belong to two projects, they may have different importance levels. If the preceding activity is more important than the succeeding activity, no problem will arise. However, if the preceding activity is less important than the succeeding activity, it will cause a problem. For example, if the less important project is canceled or postponed, the *preceding-succeeding* relationship will make the succeeding activity in the more important project unable or late to start, thus degrading the importance level of the succeeding activity and its associated project. To fix the problem, the importance level of the predecessor(s) needs to be upgraded.

The last activity in the program schedule is typically a combination of several activities such as the *termination of the projects with the first-level importance, termination of the projects with the second-level importance*, etc. Hence, when these activities with different levels of importance are combined into one single *end* activity, not all of its predecessors have to be at the same highest level of importance. Therefore, the last activity is exempted from this condition.

It is a good practice to differentiate the inherited importance level from the importance level caused by interproject connections, named as the *derived importance* in this paper. The derived importance has two attributes: an importance level and the activity (activities) from which the importance level is derived. The level of the derived importance, coming from the successor of an activity, should be higher than or equal to the inherited importance. For example, in Fig. 4, Activity E3 in Project 3 is succeeded by Activity C2 in Project 2. Because C2 has an importance level higher than that of E3, the importance levels of C2 and all its direct and indirect predecessors in Project 3 should be upgraded. Otherwise, if the less important Project 3 is cancelled, Project 2 will be affected because E3 is one of the immediate predecessors of C2. Therefore, some activities that are initially assigned with a low importance level may need to be upgraded because they are the predecessors of the more important activities. Upgrading only requires the increase of the importance level of the concerned activity to the same level as its immediate successor, or the highest importance level of all its immediate successors. When an activity is succeeded by an optional activity with higher importance, the activity from which the derived importance is obtained should also be recorded. For example, G3 in Project 3 is succeeded by A4 in Project 4 and

A4 is more important than G3 initially; therefore, the derived importance of G3 should be adjusted to a higher level. However, since A4 is optional, the derived importance of G3 is not definitive and the source of the derived importance needs to be marked.

Proposition 4

An activity with a certain importance level must be succeeded by at least one activity that has the same or higher importance level as itself.

This is named as the *pass-through-the-end* rule in this paper. The rule is also mainly used to govern interproject connections. The purpose is to ensure the integrity of the program. For example, in Fig. 4, Project 1 is followed by either Project 4 or 5 of the same importance level; if the importance levels of Projects 4 and 5 are reduced and subsequently removed, Activity F1 will become a *dangling* activity that connects to nowhere. If Project 1 is indeed independent and can fulfill its role in the program without Project 4 or 5, a direct connection between Activity F1 and the last activity of the program should be added, to logically clarify that Project 1 is independent.

Proposition 5

Except for the first and last activities, a compulsory activity must have at least one logically compulsory predecessor and at least one logically compulsory successor.

Because alternatives are introduced into the network, it needs to be assured that the compulsory activities do not lose their predecessor(s) and successor(s) due to the removal of the optional activities or projects, except for the first activity, which does not have a predecessor, and the last activity, which does not have a successor. The logically compulsory does not necessarily require that the activity connects to an actual compulsory activity or activities. As long as the preceding and succeeding relationships are logically affirmed, it meets the requirement. For example, Activity C3 in Fig. 4 is succeeded by either G3 or H3, which is optional. However, because one of them will have to be the successor of C3, C3 still has a logically compulsory activity as its successor. On the other hand, the compulsory Activity D3 in Project 3 is the predecessor for Activity H3, which is an optional activity. If H3 is removed in favor of G3, D3 will become a *dangling* activity unless it is connected to another affirmative activity such as I3.

Proposition 6

Mutually exclusive projects and activities should have the same level of direct importance.

The importance levels of activities depend on the importance levels of projects or project components upon which the activities are based. If mutually exclusive alternatives are used to meet the same needs, they should have the same level of importance. This condition is to ensure the *exchangeability* of the alternatives and nonviolation of Proposition 4. In Fig. 4, assume that Project 5 has a lower importance level than Project 4 and Project 5 is chosen in favor of Project 4 (*alternative* implies that either one of them can be chosen). Activity F1 in Project 1 will connect to an activity that has a lower importance level, hence violating Proposition 4.

Based on the propositions above, the example program schedule shown in Fig. 4 can be calculated by the following steps:

1. Specify the alternatives in the program. Unique identification codes may be assigned to the alternatives. In this paper, an alternative at the project level is represented by its project number, such as P4 and P5, while an alternative activity within a project is represented by the project number followed by an arbitrary code (e.g., P3-a1).
2. Update the importance levels of activities caused by interproject connections, i.e., the *derived importance* named in this paper. For example, E3 has an importance level of III, but because it is the predecessor of C2 with an importance level of II, *E3* and all its predecessors need to be upgraded to an importance level of II. If the derived importance is caused by an alternative, the alternative code also needs to be included. For example, Activity C3 has derived importance at Level I caused by the connection between G3 and Project 4; hence, the derived importance for C3 is written as *I(P3-a1)(P4)*, in which the first letter shows the importance level and the letters in the parentheses show the alternatives.
3. Calculate the early start (ES), early finish (ES), late start (LS), and late finish (LF) of all the activities based on the conventional CPM method. The calculation needs to take the alternatives and importance levels of the activities into consideration. Using the same example illustrated in Fig. 4, the forward and backward path calculations for Project 4 and a portion of Project 3 is presented in Fig. 5. The forward path calculation is straightforward except for those activities in Project 4. Because the early start time of the activities in Project 4 is controlled by the alternative *a1* in Project 3, the alternative number *P3-a1* needs to be labeled. When performing the backward path calculation from the end, there are three major scenarios: (1) to complete only projects of the first importance level; (2) to complete projects of the second importance level and above; and (3) to complete projects of the third importance level and above. Scenario (1) includes two options: to implement Project 4 or Project 5. Scenario (2) also includes the same two options. Scenario (3) includes three options to implement: Project 5 and Alternative 1 (a1) in Project 3, Project 5 and Alternative 2 (a2) in Project 3, and Project 4 and Alternative 1 (a1) in Project 3 [Because *a1* is the predecessor of A4 in Project 4, Alternative 2 (a2) cannot be chosen if Project 4 is selected]. In this particular example, the addition of the third importance-level project does not increase the overall program duration from the schedule that only consists of the first and second importance-level projects. Activities in Project 4 have two sets of late start/finish times as shown in Fig. 5, depending on the importance levels of projects to complete. The late finish time of Activity G3 is controlled by the late start time of two successors, A4 and I3, which can be derived from the following equation:

$$\text{Late\_finish G3} = \min\left\{\begin{matrix}10(\text{P4})(\text{I})\\ 11(\text{P4})(\text{II})(\text{III})\\ 28(\text{II})(\text{III})\end{matrix}\right\} = \min\left\{\begin{matrix}10(\text{P4})(\text{I})\\ 11(\text{P4})(\text{II})(\text{III})\\ 28(\text{P4})(\text{II})(\text{III})\\ 28(\text{P5})(\text{II})(\text{III})\end{matrix}\right\} = \left\{\begin{matrix}10(\text{P4})(\text{I})\\ 11(\text{P4})(\text{II})(\text{III})\\ 28(\text{P5})(\text{II})(\text{III})\end{matrix}\right\} \quad (1)$$

In Eq. (1), the late finish time of G3 is derived from the third-level activity I3 and is not dependent on a specific Alternative P4 or P5, while the late finish time derived from Activity A4 is only based on Alternative P4. For comparison purposes, the late finish time 28(II)(III) needs to be specified as two options: 28(P4)(II)(III) and 28(P5)(II)(III). When completing all the importance level II/III activities, if P4 is chosen, the late finish of Activity G3 will be 11 (the smaller value of 11 and 28); if P5 is chosen, the late finish time of G3 will be just 28. As can be seen in Fig. 5, different possible combinations generate different sets of late start/finish time, which

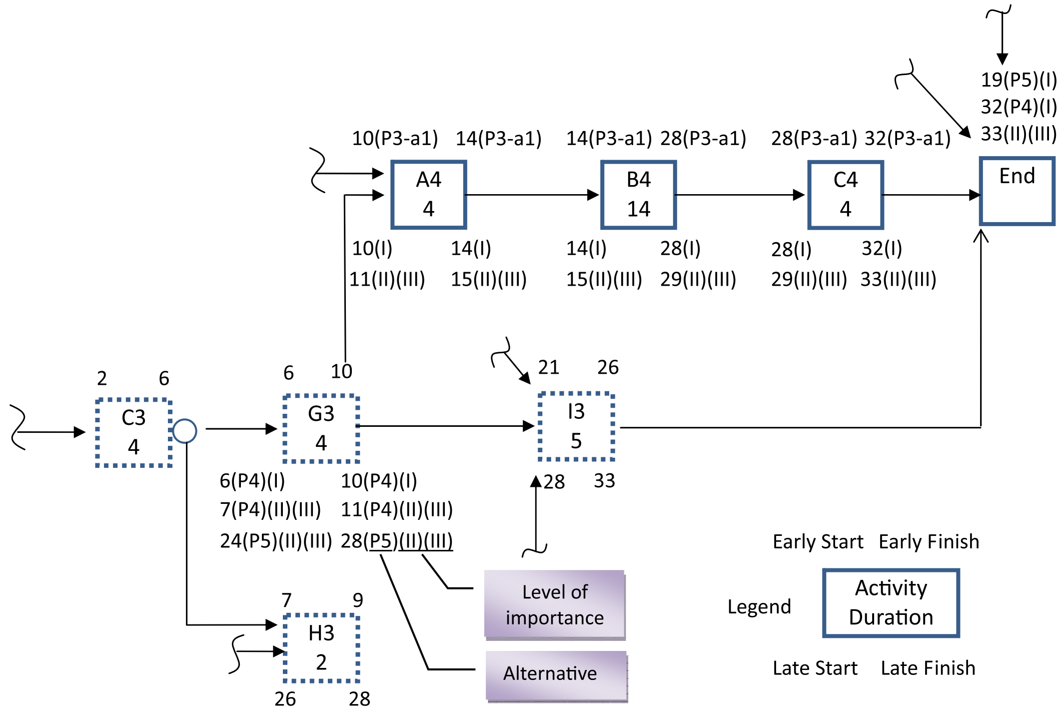

Fig. 5. Example calculation of the program schedule

provides important information for a program manager to weigh the options.

Step 4: Analyze and Optimize the Program Schedule

The calculation results of the entire program schedule in Fig. 4 are summarized and shown in Table 1. For each activity, the table shows: (1) the project to which the activity belongs, (2) the initial activity importance level that is inherited from the project importance level determined at the planning stage, (3) the derived importance level caused by interproject connections, (4) alternative code, and (5) the CPM times (ES, EF, LS, LF) and total float. Unlike the conventional CPM schedule, the activity times also show the alternatives and importance levels that are associated with the calculated results. The information in Table 1 may be used to analyze and optimize the program based on funding and time constraints.

First, the results provide the total durations of the program in different scenarios. For example, if only the first-level projects are implemented and Alternative P5 is chosen, the total duration of the program is 19. If Alternative P4 is executed, the total duration becomes 32. If the second-level project is implemented, the total duration is 33, and the inclusion of the third-level project will not further increase the program duration. The program manager can choose the right combination of projects and alternatives to meet the time objective.

Secondly, for each individual activity, its inherited importance level, the importance level caused by interproject connections, and its connection with other activities or projects can be clearly seen. In addition, the calculation generates the start and finish times and floats of activities with respect to different importance levels and alternatives. Such information provides program managers the *deadlines* of choosing and implementing the program activities in response to different scenarios. For example, if only projects with importance Level 1 are considered and Project 4 and the first alternative in Project 3 are chosen, C3 in Project 3 needs to start on Day 2 with no float. If projects with all the levels of importance are considered and the first alternative in Project 3 (P3-a1) and Project 4 are chosen, the late start time for C3 is Day 3, with one day of float. If projects with all the importance levels are considered and P3-a1 and Project 5 are chosen, the late start time for C3 is Day 20, with 18 days of float. If projects with all importance levels are considered and P3-a2 is chosen, the late start time for C3 is Day 22, with 20 days of float.

Thirdly, if the activities are loaded with cost information, the program costs of implementing projects of different importance levels and alternatives can be easily calculated and subsequently evaluated. Such information, combined with time information, can assist decision makers in identifying projects and alternatives that satisfy the program's key objectives without exceeding the budget. The integration of time and costs are believed to be essential for project success (e.g., Cho et al. 2010).

Fourthly, the program schedule highlights the portion of a project that is more important than the rest part of the same project caused by interproject connections. For example, the importance levels of Activities B3 and E3 are initially the lowest, but because they are predecessors of Activity C2 in another project, their importance levels are upgraded to Level II. If a budget cut causes the Level III project to be terminated, at least B3 and E3 should be kept. Such a situation is not uncommon in a construction program. For instance, assume that one of the projects in a program is to build a city square with sculptures and fountains as well as new buildings. Budget constraints may place the sculpture and fountain portions of the projects on hold, but the site construction and underground utilities may remain unchanged because they are essential for the nearby buildings.

Step 5: Update Program Schedule

The program schedule as shown in Fig. 4 needs to be frequently updated to promptly reflect the progress and changes in the program. As the program proceeds, it soon loses some flexibility and options. For example, once A5 in Project 5 is started, all

Table 1. Result of Schedule Calculation

Act	Project	Orginal importance	Derived importance	Alternatives	ES	EF	LS	LF	TF
A1	1	I	/	/	0	3	3(P4)(I); 4(P4)(II)(III)0(P5)(I); 14(P5)(II)(III)	6(P4)(I); 7(P4)(II)(III)3(P5)(I); 17(P5)(II)(III)	3(P4)(I); 4(P4)(II)(III)0(P5)(I); 14(P5)(II)(III)
B1	1	I	/	/	0	3	3(P4)(I); 4(P4)(II)(III)0(P5)(I); 14(P5)(II)(III)	6(P4)(I); 7(P4)(II)(III)3(P5)(I); 17(P5)(II)(III)	3(P4)(I); 4(P4)(II)(III)0(P5)(I); 14(P5)(II)(III)
C1	1	I	/	/	0	2	4(P4)(I); 5(P4)(II)(III)1(P5)(I); 15(P5)(II)(III)	6(P4)(I); 7(P4)(II)(III)3(P5)(I); 17(P5)(II)(III)	4(P4)(I); 5(P4)(II)(III)1(P5)(I); 15(P5)(II)(III)
D1	1	I	/	/	3	6	6(P4)(I); 7(P4)(II)(III)3(P5)(I); 17(P5)(II)(III)	9 (P4)(I); 10(P4)(II)(III)6(P5)(I); 20(P5)(II)(III)	3(P4)(I); 4(P4)(II)(III)0(P5)(I); 14(P5)(II)(III)
E1	1	I	/	/	3	5	7(P4)(I); 8(P4)(II)(III)4(P5)(I); 18(P5)(II)(III)	9 (P4)(I); 10(P4)(II)(III)6(P5)(I); 20(P5)(II)(III)	4(P4)(I); 5(P4)(II)(III)1(P5)(I); 15(P5)(II)(III)
F1	1	I	/	/	6	7	9(P4)(I); 10(P4)(II)(III)6(P5)(I); 20(P5)(II)(III)	10(P4)(I); 11(P4)(II)(III)7(P5)(I); 21(P5)(II)(III)	3(P4)(I); 4(P4)(II)(III)0(P5)(I); 14(P5)(II)(III)
A2	2	II	/	/	0	7	3	10	3
B2	2	II	/	/	7	14	10	17	3
C2	2	II	/	/	15	23	15	23	0
D2	2	II	/	/	14	24	17	27	3
E2	2	II	/	/	23	27	23	27	0
F2	2	II	/	/	27	33	27	33	0
A3	3	III	III(P3-a1)(P4)	/	0	2	0(P3-a1)(P4)(I)0(II)(III)	2(P3-a1)(P4)(I)2(II)(III)	0(P3-a1)(P4)(I)0(II)(III)
B3	3	III	II	/	2	8	2(II)(III)	8(II)(III)	0(II)(III)
C3	3	III	IIII(P3-a1)(P4)	/	2	6	2(P3-a1)(P4)(I) 3(P3-a1)(P4)(II)(III) 20(P3-a1)(P5)(II)(III) 22(P3-a2)(P5)(II)(III)	6(P3-a1)(P4)(I) 7(P3-a1)(P4)(II)(III) 24(P3-a1)(P5)(II)(III) 26(P3-a2)(P5)(II)(III)	0(P3-a1)(P4)(I) 1(P3-a1)(P4)(II)(III) 18(P3-a1)(P5)(II)(III) 20(P3-a2)(P5)(II)(III)
D3	3	III	III	/	2	7	23(P3-a1)21(P3-a2)	28(P3-a1)26(P3-a2)	21(P3-a1)19(P3-a2)
E3	3	III	II	/	8	15	8(II)(III)	15(II)(III)	0(II)(III)
F3	3	III	III	/	15	21	22	28	7
G3	3	III	I(P3-a1)(P4)	P3-a1	6	10	6(P4)(I)7(P4)(II)(III) 24(P5)(II)(III)	10(P4)(I)11(P4)(II)(III) 28(P5)(II)(III)	0(P4)(I)1(P4)(II)(III) 18(P5)(II)(III)
H3	3	III	III	P3-a2	7	9	26	28	19
I3	3	III	III	/	21	26	28	33	7
A4	4	I	/	P4	10(P3-a1)	14(P3-a1)	10(I)11(II)(III)	14(I)15(II)(III)	0(I)1(II)(III)
B4	4	I	/	P4	14(P3-a1)	28(P3-a1)	14(I)15(II)(III)	28(I)29(II)(III)	0(I)1(II)(III)
C4	4	I	/	P4	28(P3-a1)	32(P3-a1)	28(I)29(II)(III)	32(I)33(II)(III)	0(I)1(II)(III)
A5	5	I	/	P5	7	11	7(I)21(II)(III)	11(I)25(II)(III)	0(I)14(II)(III)
B5	5	I	/	P5	11	15	11(I)25(II)(III)	15(I)29(II)(III)	0(I)14(II)(III)
C5	5	I	/	P5	15	19	15(I)29(II)(III)	19(I)33(II)(III)	0(I)14(II)(III)
END	/	I	/	/	19(P5)(I) 32(P4)(I) 33(II)(III)	19(P5)(I) 32(P4)(I) 33(II)(III)	19(P5)(I) 32(P4)(I) 33(II)(III)	19(P5)(I) 32(P4)(I) 33(II)(III)	

Note: Act = activity code; Alt = code for alternatives; Der. Imp = derived importance level; EF = early finish; ES = early start; LF = late finish; LS = late start; Org. Imp = original importance level; Pro = project number; TF = total float.

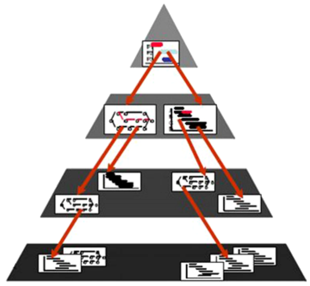

Fig. 6. Multilevel hierarchical network schedule

the activities in Project 4 need to be removed. The connections between Project 4 and Project 3 will also be removed. Besides the decisions on alternatives, there may be other changes in the program schedule such as changes in activity durations, importance levels, and logical connections between the activities. All the changes need to be incorporated into the updated program schedule, followed by recalculating the network schedule.

Application of the Proposed Scheduling Method

Hallmark events such as the Olympics and World Expo are often used by countries or local governments as opportunities to boost economy and urban redevelopment (Essex and Chalkley 1998). The success of the hallmark events is affected by the costs and delivery time of the infrastructures built to support such events. Facility construction of this type usually involves a large number of interrelated projects. Therefore, these projects are better to be managed as a program, instead of a single megaproject. Such programs are usually publicly funded or subsidized and hence affected by public financing procedures and regulations, macroeconomic conditions, and even the political environment. There are also multiple stakeholders involved in the programs. For example, for the Shanghai World Expo, a large number of buildings were funded by foreign companies and designed and constructed by foreign countries. These characteristics make the programs subject to numerous changes and uncertainties, yet the programs still have fixed deadlines set by the events. Therefore, integrated time and cost management of these programs poses a challenge for program managers.

A hierarchical network as shown in Fig. 6 was used to schedule the construction program for the 2010 Shanghai World Expo. At Level I, the controlling start and completion dates were specified for major projects and subprograms, which were derived from the work breakdown structure (WBS). At Level II, the schedules for projects and subprograms were expanded to include major milestones. At Level III, comprehensive schedules were developed for each zone of the program. At Level IV, detailed schedules were developed for each project or subprogram. Although sequential relationships were developed for the schedules at Levels II, III, and IV, respectively, these relationships were not mapped to schedules at different levels. As a result, schedule change at a certain level was not automatically reflected in the entire program schedule.

Incorporating options and importance levels into the program schedule could create flexibility for more efficient management, helping address various challenges including complex scope, fixed deadline, and constraint budget. For instance, the program cost and schedule may have been better managed if the projects were assigned with different importance levels, based on their contributions to the key program goals. The Shanghai World Expo program had multiple goals with different priorities. As mentioned previously, multicriteria decision analysis (MCDA) techniques could have been used to rank the projects under the prioritized program goals. The ranking scores could then be used to help determine the importance levels of the projects. For example, one project in the program was to build two VIP ferry terminals with a planned duration of more than one year. Compared to many other projects such as the Expo Theme Pavilion, the ferry terminals were less important. When time and funding became tight, as occurred at the end of the Expo construction program, priority was given to projects that served the core functions of the program. However, projects with low priority, or a portion of the projects with low priority, became necessary because of interproject connections. The proposed technique would make it easy to examine the sensitivity of the program durations and costs to the inclusion or removal of the terminal construction project. In addition, time, floats, and connections between the individual activities for the projects could have been easily retrieved.

Due to the size limit of the paper, the entire schedule of the Shanghai World Expo construction program is not included. Two projects in Fig. 7 are used to conceptually illustrate the feasibility of incorporating options and importance levels in program scheduling. One of the projects is the construction of the *China Pavilion* and the other is the construction of the transport facilities near the China Pavilion. First, different importance levels are assigned to the two projects. Secondly, options were added to the two projects and the impacts of the options on program schedule and cost are assessed accordingly. For example, the upper structure of the China Pavilion could be built with steel or concrete. If the steel structure were used, it would need a longer lead time for the development of shop drawings, fabrication, and transportation of the structure members, even though this process could be carried out parallel with other activities. Once the steel members were delivered to the site, they could be assembled and be lifted by cranes. This could potentially accelerate the project schedule in comparison to concrete construction. However, assembly of the steel structures required occupying the site where the transport project was located, whereas the use of the concrete structure might not require this space. By adding these two options and performing CPM calculation, the effects of the options on time, costs, and other projects may be assessed. Similarly, a portion of the transportation facilities that accommodate pedestrians crossing the road may have three options: an underground tunnel, a footbridge, or just traffic lights. These various options result in different program cost and duration, as shown in Table 2.

The inclusion of options, interproject connection, and importance information in the program schedule may also help optimize the use of resources. In the Shanghai Expo construction, more than 400 new buildings were constructed in a short period of time. If most buildings used concrete structures, the local ready-mixed concrete plants may not have the sufficient capacity at the peak construction time. The proposed program scheduling technique can be used to analyze the amount of concrete needed at different time and

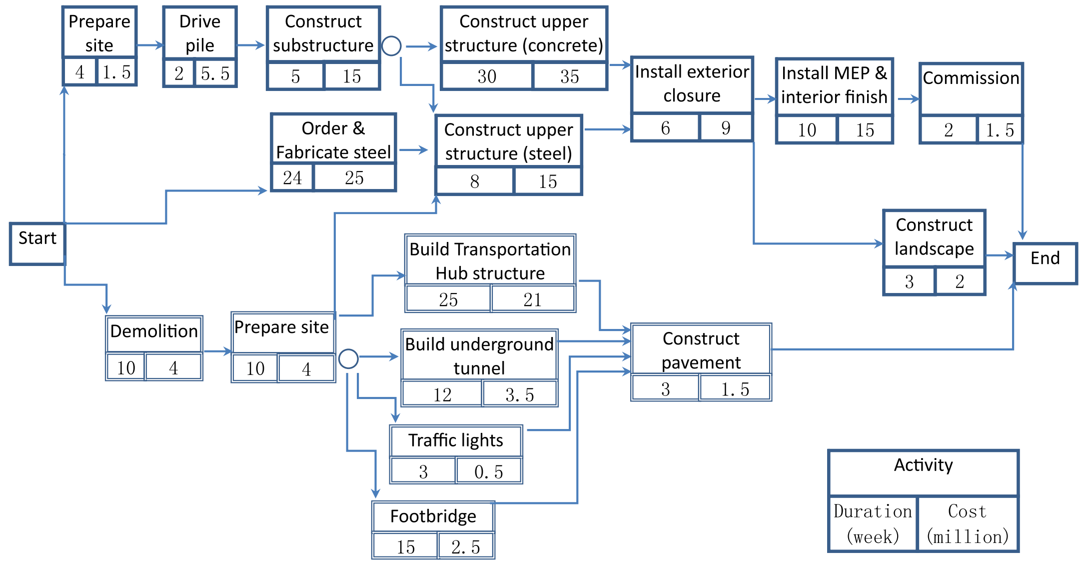

Fig. 7. Example of program schedule segment

Table 2. Summary of Calculation Result for the Schedule in Fig. 7

Importance level	Alternative		Completion time (week)	Cost (million)
1	Concrete structure		59	84.5
1	Steel structure		50	90.5
2	Concrete structure	Tunnel	59	118.5
2		Traffic lights	59	115.5
2		Footbridge	59	117.5
2	Steel structure	Tunnel	50	116.5
2		Traffic lights	50	113.5
2		Footbridge	50	115.5

optimize the use of resource by choosing alternative structures or facilities, in addition to adjusting project (activity) start and completion time.

Conclusion and Discussion

Lack of a special methodology to handle the unique issues and challenges in construction programs is the Achilles' heel in program management. One particular area that needs to be improved is the management of priorities, uncertainties, and interproject connections in a program environment. Because time management of programs is still largely dependent on the techniques developed for managing a single project, the information provided for program managers is quite limited.

A new approach to program scheduling is developed and presented in this paper. This approach enables program managers to incorporate priorities and alternatives into a schedule, thus improving planning flexibility in the dynamic and risky program environment. Theoretical foundation and methods for performing CPM calculations are developed for this approach, and examples are used to illustrate the concepts and the techniques. It was found that richer and more sensible scheduling information can be obtained from this new technique. Although the manual CPM calculation of the proposed method appears to be more complicated than that of the conventional method, the algorithms can in fact easily be implemented in a computer program to facilitate its application.

The discussion in this paper is based on some simplified examples, and the relationships between the activities are all finish-to-start and no specific limit is imposed on the use of resources. The effects of relaxing these assumptions on the proposed method may be further studied.

Acknowledgments

The paper is supported by a project at the Hong Kong Polytechnic University (1-ZV8H).

References

Archer, N. P., and Ghasemzadeh, F. (1999). "An integrated framework for project portfolio selection." *Int. J. Project Manage.*, 17(4), 207–216.

Artto, K. A., Martinsuo, M., Gemünden, H. G., and Murtoaro, J. (2009). "Foundations of program management: A bibliometric view." *Int. J. Project Manage.*, 27(1), 1–18.

Barrie, D. S., and Paulson, B. C. J. (1992). *Professional construction management: Including contracting CM, design-construct, and general contracting*, McGraw-Hill, New York.

Chang, A. S. (2002). "Reasons for cost and schedule increase for engineering design projects." *J. Manage. Eng.*, 10.1061/(ASCE)0742-597X(2002)18:1(29), 29–36.

Cho, K., Hong, T., and Hyun, C. (2010). "Integrated schedule and cost model for repetitive construction process." *J. Manage. Eng.*, 10.1061/(ASCE)ME.1943-5479.0000009, 78–88.

Davenport, A. J., Gefflot, C., and Beck, J. C. (2001). "Slack-based techniques for robust schedules." *Constraints and Uncertainty Workshop, 7th Int. Conf. on Principles and Practice of Constraint Programming*, Paphos, Cyprus.

Demeulemeester, E. L., and Herroelen, W. S. (2002). *Project scheduling: A research handbook*, Kluwer Academic Publishers, Boston.

Essex, S., and Chalkley, B. (1998). "Olympic games: Catalyst of urban change." *Leisure Stud.*, 17(3), 187–206.

Figueira, J. R., Greco, S., and Ehrgott, M. (2005). *Multiple criteria decision analysis: State of the art surveys*, Springer, Berlin, Heidelberg, New York.

Goldratt, E. M. (1997). *Critical chain*, North River Press , Great Barrington, MA.

Hall, N., and Posner, M. (2004). "Sensitivity analysis for scheduling problems." *J. Scheduling*, 7, 49–83.

Herroelen, W., and Leus, R. (2005). "Project scheduling under uncertainty: Survey and research potentials." *Eur. J. Oper. Res.*, 165(2), 289–306.

Johnston, D. W. (1981). "Linear scheduling method for highway construction." *J. Constr. Div.*, 107(2), 247–261.

Kelly, J. E. (1961). "Critical path planning and scheduling mathematical bases." *Oper. Res.*, 9(3), 246–320.

Khodakarami, V., Fenton, N., and Neil, M. (2007). "Project scheduling: Improved approach to incorporate uncertainty using Bayesian networks." *Project Manage. J.*, 38(2), 39–49.

LA Metropolitan Transportation Authority. (2012). "Overview: Measure R works for LA." ⟨http://www.metro.net/projects/measurer/overview/⟩ (Jan. 12, 2012).

Malcolm, D. G., Roseboom, J. H., Clark, C. E., and Fazer, W. (1959). "Application of a technique for research and development program evaluation." *Oper. Res.*, 7(5), 646–669.

Mehta, S. V., and Uzsoy, R. (1999). "Predictive scheduling of a single machine subject to breakdowns." *Int. J. Comput. Integr. Manuf.*, 12(1), 15–38.

Orouji, H., Haddad, O., Fallah-Mehdipour, E., and Mariño, M. (2014). "Extraction of decision alternatives in project management: Application of hybrid PSO-SFLA." *J. Manage. Eng.*, 10.1061/(ASCE)ME.1943-5479.0000186, 50–59.

PMI (Project Management Institute). (2008). *The standard for program management*, 2nd Ed., Newtown Square, PA.

Saaty, T. L. (2005). *Theory and applications of the analytic network process: Decision making with benefits, opportunities, costs, and risks*, 3rd Ed., RWS Publications, Pittsburgh.

Sabuncuoglu, I., and Bayiz, M. (2000). "Analysis of reactive scheduling problems in a job shop environment." *Eur. J. Oper. Res.*, 126(3), 567–586.

Sanghera, P. (2008). *Fundamentals of effective program management: A process approach based on the global standard*, J. Ross Publishing, Fort Lauderdale, FL.

Slowinski, R., and Hapke, M. (2000). *Scheduling under fuzziness*, Physica, Heidelberg, Germany.

Song, L., Mohamed, Y., and Abou Rizk, S. M. (2009). "Early contractor involvement in design and its impact on construction schedule performance." *J. Manage. Eng.*, 10.1061/(ASCE)0742-597X(2009)25:1(12), 12–20.

Szelke, E., and Kerr, R. M. (1994). "Knowledge-based reactive scheduling." *Prod. Plann. Control*, 5(2), 124–145.

Wagner, P. (2009). *Global program management*, McGraw-Hill Professional, New York.

Weber, S. C. (2004). *Scheduling construction projects: Principles and practices*, Prentice Hall, Upper Saddle River, NJ.