Graphical Approach for Manpower Planning in Infrastructure Networks

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Abstract: Infrastructure networks such as highways and pipelines have recently been at the center of attention for contractors and owner organizations. Due to their large size and their repetitive/distributed nature, construction and/or maintenance operations for such networks become complex tasks that require huge resources, particularly manpower. In order to provide a transparent tool for quick manpower planning and sensitivity analysis, a graphical approach (using nomographs) is introduced in this paper. The nomographs encode the mathematical formulation, and the results of many optimization experiments, of a distributed model for scheduling large projects with multiple sites. Accordingly, the nomographs can be readily utilized by practitioners to estimate the manpower needed to meet a predefined deadline, under anticipated network-level risks due to unfavorable site conditions. Details on the development of the nomographs are presented in the paper along with an example to demonstrate their usefulness for supporting manpower planning decisions and for what-if analysis. The nomographs also present researchers with a simple yet powerful approach to make research results readily usable by practitioners.

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Introduction

Manpower planning is a major scheduling objective in all projects. The manpower planning process, however, is not a simple task, particularly for infrastructure networks that are large in size and involve multiple scattered sites with varying work conditions. Examples of these networks include highways, bridges, airports, water/sewer systems, and buildings. Traditionally, manpower planning decisions for infrastructure projects are determined based on experience on past projects, with little support from existing tools. This, however, represents a major challenge for construction managers, particularly due to the stringent resource and time constraints on operations and the increasing calls for efficiency and cost savings. Such savings can only be attained by considering the particular needs of infrastructure networks.

As compared with traditional projects, planning the construction/maintenance operations in infrastructure networks is a much bigger challenge due to the multisite distributed nature of the work: The varying work conditions from one site to the other; and the stringent time and resource constraints on the execution of infrastructure projects. As such, the key decisions that relate particularly to infrastructure projects are the number of crews to use, the construction method to employ in each task, and the order of execution of each site.

Most of the planning and scheduling tools available at the commercial and research levels address some but not all aspects of infrastructure project management. For a detailed literature review of the various models developed for scheduling repetitive projects, the reader is referred to Elhakeem (2002). Recently, a new distributed scheduling method (DSM) (Hegazy et al. 2004) has been introduced to facilitate the planning of resources in distributed and repetitive projects. The model is flexible and considers all project parameters as variables to be optimized using the genetic algorithms technique. The model has been implemented in a computer program (*BAL*, copyrighted to the second writer) that is used in the present study.

Distributed Scheduling Model

DSM is a resource-driven model that determines the optimum amount of resources to be employed in construction/maintenance operations involving multiple distributed sites that have different work conditions and work quantities. The main features of DSM are:

1. Has a database of resources that are used to generate cost and duration estimates;
2. Shows a clear multiple-site schedule with color coded crews;
3. Allows for varying the site order, and for considering site productivity factors;
4. Allows for up to three methods of construction for each activity (each method has specific resources, duration, and cost);
5. Allows activities to have varying quantity of work from one site to the other; and

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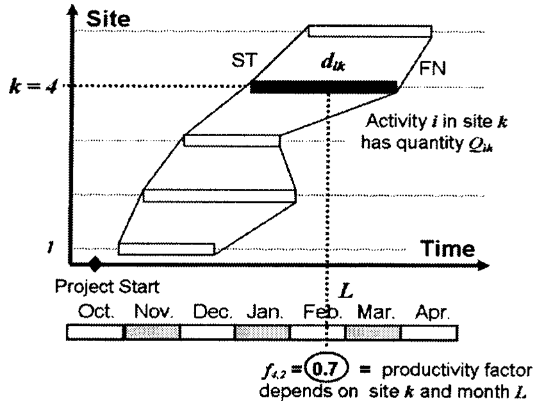

Fig. 1. Activity identification parameters

6. Incorporates an algorithm for minimizing total cost and assigning crews to sites.

Manpower Calculations in the Distributed Scheduling Model

In the DSM, the manpower necessary to meet a deadline is calculated in two steps:

1. Estimating activities' durations and costs; and
2. Calculating the manpower, assuming favorable work conditions at the various sites.

These two aspects (described below) represent the basic manpower calculations. It is noted that the DSM and its (*BAL*) implementation do not provide a direct formulation to calculate manpower under unfavorable site conditions. Rather, the manpower adjustment is made through the DSM's optimization feature, and is dealt with later.

For basic manpower calculations, activities' durations are first estimated. The duration d_{ik} of activity i in site k is calculated as follows, with activity parameters shown in Fig. 1:

$$d_{ik} = \frac{Q_{ik}}{P \times f_{kL}} \tag{1}$$

where Q_{ik}=quantity of work in site k; P represents the production rate for the resources involved; and f_{kL}=productivity factor (0 to 100%) depending on the work conditions in site k during month $L(1, 2, \ldots, 12)$ in which the activity is scheduled.

With the duration d_{ik} being estimated using Eq. (1), the number of crews C_i for each activity i needed to meet a specified deadline duration DL under favorable work conditions can be determined from the desired rate of progress R, as follows (Hegazy 2002):

$$C_i = \text{RoundUp}(R_i \times d_{ik}); \quad C_i \leqslant \text{Maximum available crews} \tag{2}$$

The progress rate R_i itself is determined based on the deadline duration DL, as follows (Fig. 2, Hegazy 2002):

$$R_i = \frac{S - 1}{(\text{DL} - \text{CPM}_o) + \text{TF}_i} \tag{3}$$

where S=total number of sites; and TF_i=total float of activity i. In essence, Eq. (3) specifies that if one site takes the duration of its critical path method (CPM) network CPM_o, to be completed, then, the remaining $(S-1)$ sites will take the remaining time $(\text{DL}-\text{CPM}_o)$, with the rate of progress R_i that is slightly relaxed according to activity float.

From Eqs. (2) and (3), a single formulation for the crews C_i needed for an activity i is:

$$C_i = \text{RoundUp}\left\{ d_{ik} \times \left(\frac{S-1}{\text{DL} - \text{CPM}_o + \text{TF}_i} \right) \right\}$$

$$C_i \leqslant \text{Maximum available crews} \tag{4}$$

This equation can then be represented graphically in a nomograph.

Basic Manpower Nomograph

To simplify the process of manpower planning, a nomograph encoding Eq. (4) is developed to determine the number of crews C_i needed to meet deadline under favorable site conditions.

Nomograph Drawing Rules

A nomograph is a simple graphical representation of any mathematical formulation. A basic mathematical operation such as subtraction can be represented in a *nomograph* as shown in Fig. 3. To represent the $(C=A-B)$ formulation involves the following:

- Using a different scale to represent each of the three variable in the equation (e.g., Scale 1 for A, Scale 2 for B, and Scale 3 for C);
- Arranging the three scales relative to each other (parallel, inclined, etc.);
- Deciding the spacing and type of each scale (linear, logarithmic, etc.); and

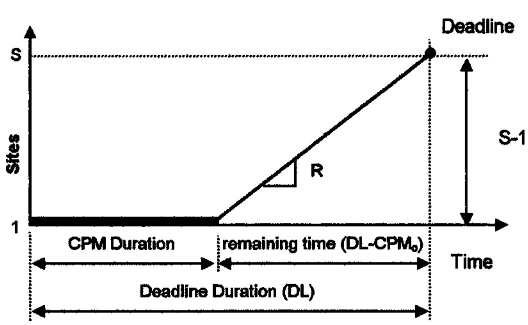

Fig. 2. Calculating a desired progress rate (R)

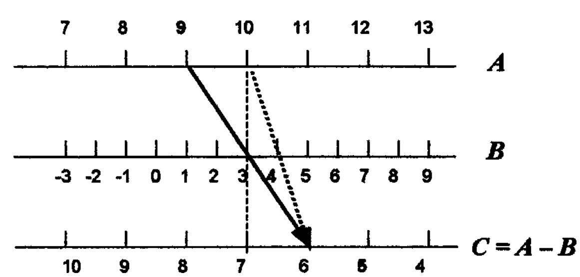

Fig. 3. Subtraction operation using a nomograph

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- Designing the numbering direction and range of each scale. Other operations such as addition, division, and multiplication can also be converted into a subtraction form, and drawn using the nomograph. The conversion is as follows:
- Addition is a negative subtraction, $A+B=A-(-B)$;
- Division is a logarithmic subtraction, $\log(A/B)=\log A-\log B$. As such, the variables A and B are drawn on logarithmic scales using the logarithmic cycle width instead of the spacing expression; and
- Multiplication is a logarithmic addition, $\log(A\times B)=\log A+\log B$, afterward, the addition can be converted into a subtraction form as shown earlier.

Basic Nomograph

Using the nomograph rules, Eq. (4) that determines the number of crews C_i necessary to meet a given deadline was represented in the form of a nomograph as shown in Fig. 4. In doing so, Eq. (4) was decomposed into the following suboperations:

$$V1 = \mathrm{CPM}_o - \mathrm{TF}_i; \quad V2 = \mathrm{DL} - V1$$

$$V3 = (S-1)/V2; \quad \text{and} \quad C_i = V3 \times d_{ik}$$

where $V1$, $V2$, and $V3$=intermediate calculations (indicated on the nomograph). As such, two subtractions, one division, and one multiplication were used in the nomograph.

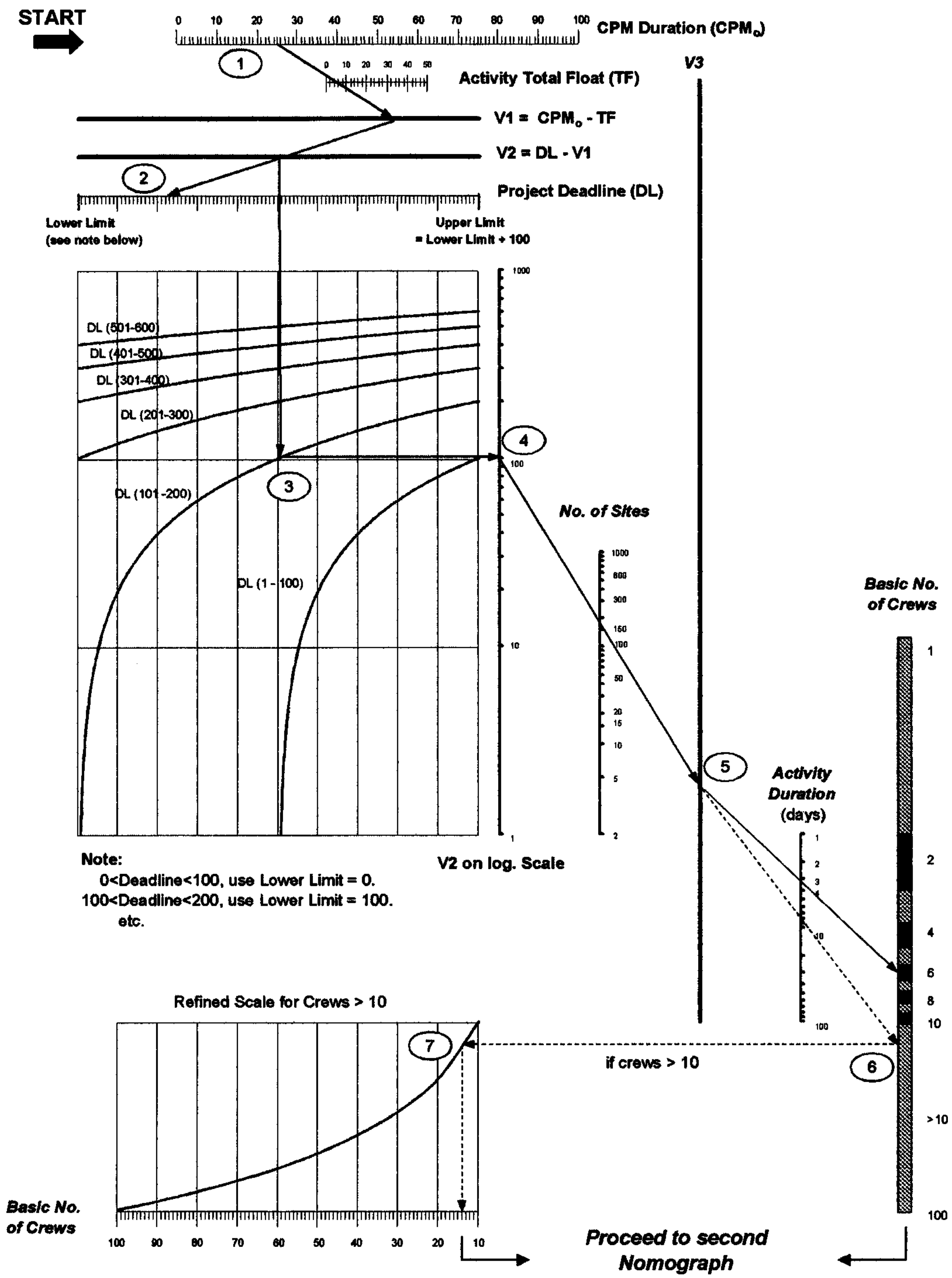

Fig. 4. Nomograph of basic manpower planning

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The basic nomograph can be easily used to determine the number of crews required for the construction of one activity at a time. To use the nomograph, the flow of arrows in Fig. 4 should be followed. It is noted that the deadline DL scale is designed to take a flexible range. It is noted also that if the number of crews is greater than 10, the crews scale becomes less accurate and, therefore, a refined scale is provided to the left.

Network Risk and Consequent Project Delay

An important aspect to consider in scheduling crews around scattered sites is the variability of work conditions among the sites, which affect tasks' durations and the overall project duration. As such, the number of crews determined using favorable work conditions might not be sufficient to meet the specified deadline. Accounting for the variability in site conditions, however, is not a simple task. Even if conditions are known at the site level, their impact on the overall construction program may not be understood. To represent site conditions, it is possible to use monthly productivity factors (>0 to 100%) to represent not only weather but also other conditions that hinder productivity, such as site access, remoteness, local bylaws, labor shortage, safety issues, etc. This approach, shown in an example of 10 sites in Table 1, is a reasonable approximation of site condition. One possible approach to determine the productivity factors is to analyze historical data of comparable work crews under different seasons and/or work conditions. Once determined, the monthly factors can then be used to refine activity duration during the scheduling process using Eq. (1). It is noted that if an activity stretches along more than one month, then weighted factors can be used.

When productivity factors are less than 100%, crews will take longer duration to finish tasks and as such, the project duration is expected to be extended beyond the deadline. So, the amount of manpower calculated using Eq. (4) underestimates the number of crews needed to meet project deadline. To meet the project deadline in this case, the manpower (number of crews) will need to be increased to compensate for the project delays. Practically, however, with a network of a large number of sites, it is cumbersome to use all the monthly productivity factors at all individual sites as part of an equation to determine a crew adjustment formulation. Thus, aggregate network-level, rather than site-level, indicators of work conditions need to be introduced to simplify the analysis. Accordingly, two indicators of the network—risk severity and extent—are introduced.

Table 1. Site Productivity Factors

Site	January (%)	⋯	October (%)	November (%)	December (%)
	Construction period				
S1	70	⋯	80	80	75
S2	100	⋯	100	100	100
S3	60	⋯	100	70	65
S4	70	⋯	70	60	70
S5	100	⋯	100	100	100
S6	95	⋯	100	100	100
S7	75	⋯	80	100	100
S8	80	⋯	100	100	100
S9	75	⋯	100	100	100
S10	100	⋯	100	100	100

1. The network risk severity (NRS) is measured as the average of all productivity losses during the construction period (analogous to the mean of a normal distribution):

$$\text{NRS} = (100\,\% - \text{Average of all productivities during the construction period}) \tag{5}$$

   Using the data of Table 1, the average of productivities during the construction period is calculated to be 91.67% and accordingly, the $\text{NRS}=100-91.67=8.33\%$.
2. The network risk extent (NRE) is measured as the percentage of sites with low monthly productivity factors (analogous to the standard deviation of a normal distribution):

$$\text{NRE} = 100 \times \frac{\text{Number of sites with low productivity}}{\text{Total number of sites}} \tag{6}$$

   For example, based on the information provided in Table 1, the construction period is the three months of October, November, and December. In that period, the number of sites that have productivities of less than 100% is four out of the total ten sites. Hence, the NRE is calculated as 4/10 or 40%.

It is noted that both NRE and NRS indicators are necessary. The risk extent NRE can only express how wide is the productivity loss problem, but does not indicate how severe is the loss, which is represented by the NRS. Conversely, a 20% NRS does not indicate whether the productivity loss is concentrated in one site or distributed among a group of sites. The NRE, therefore, is needed to indicate the risk extent.

Project Delay due to Productivity Loss

When a network is exposed to a certain productivity loss (indicated by a set of NRE and NRS values), it will consequently exhibit a percentage delay calculated as follows:

$$\text{Project Delay}(\%) = 100 \times \left(\frac{\text{Project Duration} - \text{Project Deadline}}{\text{Project Deadline}}\right) \tag{7}$$

For various values of NRE and NRS, the delay percentage de-

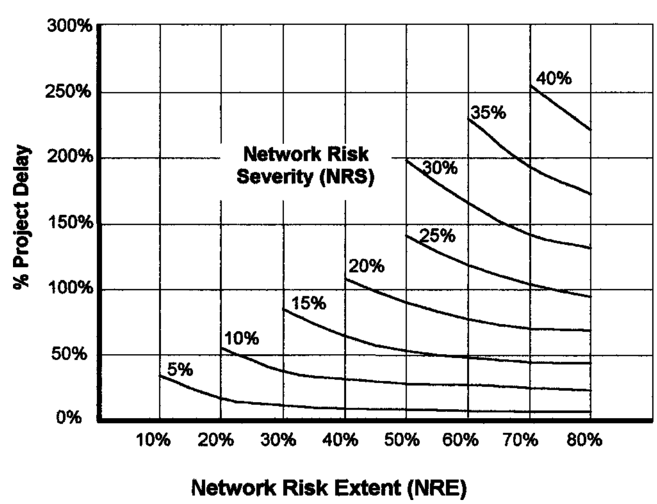

Fig. 5. Effect on network risk on project delay

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scribes the schedule variability under risk, as shown in Fig. 5. The figure was generated based on experimental results involving three hypothetical projects of 30, 120, and 210 sites (to consider different numbers of sites). A typical site has 11 activities (CPM shown in Fig. 6) and 32-day duration. In order to study only the impact of productivity loss, many parameters such as the work quantity at every site were kept constant (average of the quantities at all sites). For each of the three projects, a range of network conditions was experimented with and consequent delays evaluated. Each number in Table 2 represents the delay [calculated using Eq. (7)] associated with a combination of NRE and NRS values (indicating one network state of productivity loss). It is noted that not all combinations of NRE and NRS values are possible (Blanks in Table 2) due to the fact that high NRS values do not happen at low NRE values.

As shown in Table 2, 39 different network conditions were experimented with for each of the 30-, 120-, and 210-site projects (total of 117 experiments). To arrive at the delay values associated with each experiment, the corresponding NRE and NRS values were converted to monthly factors in the individual sites in a manner that is consistent with Eqs. (5) and (6). For example, in the case of the 30 sites, to arrive at a network condition of (NRE=30%, NRS=10%), 9 random sites (representing NRE =30%) were selected and their productivity values from October to December were set to 66.7%, thus the NRS becomes 10% [Eq. (5)].

Once the site productivity factors associated with a network condition were known, they were then entered into program *BAL* which automatically calculates modified activity durations and determines the consequent project delay beyond deadline (64, 160, and 256 days for the 30, 120, and 210 sites, respectively). The process of adjusting productivities, using *BAL*, and calculating delays was repeated for the 117 experiments.

Manpower Adjustment to Recover Project Delay

As mentioned earlier, program *BAL* was useful in calculating the project delay under a given network productivity condition. *BAL*, however, does not directly determine the crew adjustment that eliminates delays and meets deadline. To compensate for the delays, the number of crews determined for favorable working conditions [C_i, Eq. (4)] can be adjusted using a crew correction factor CCF, as follows:

$$C_{im} = \text{CCF} \times C_i \tag{8}$$

where C_{im} is the modified number of crews that meet the deadline. As a scheduling strategy to increase the number of crews, a simple modification is introduced to the progress rate calculation,

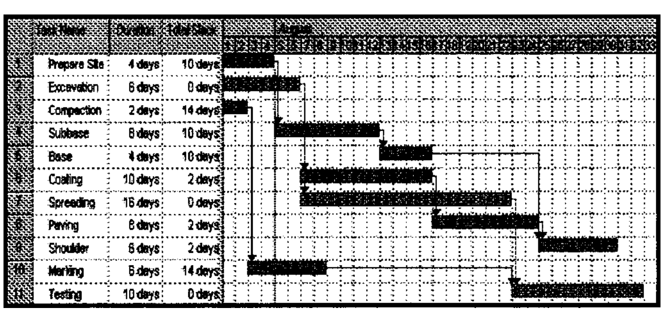

Fig. 6. Typical activities and logical relationships

Table 2. Percentage Project Delay under Various Network Conditions

Network risk extent	Network risk severity 5%	10%	15%	20%	25%	30%	35%	40%
10%	40.8							
20%	19.2	49.7						
30%	12.2	31.6	69.2					
40%	9.7	24.8	48.4	85.5				
50%	8.1	21.1	41.3	70.0	111.3	159.2		
60%	7.0	19.7	36.3	56.4	91.3	121.6	169.5	
70%	5.0	18.4	31.3	54.7	74.7	102.7	144.1	184.8
80%	4.8	16.3	30.3	50.0	70.2	99.5	128.8	160.9

Note: Number of sites=30 and deadline=64 days.

as shown in Fig. 7. In the figure, increasing the original CPM length CPM_o by a factor Z (i.e., $\text{CPM}_m = Z \times \text{CPM}_o$), results in a steeper progress slope R_m which leads to a larger number of crews. Mathematically, Fig. 7 introduces a modification to Eq. (4) when applied to critical activities (TF=0), as follows:

$$C_{im} = \text{RoundUp}\left\{ d_{ik} \times \left(\frac{S-1}{\text{DL} - (Z \times \text{CPM}_o)} \right) \right\}$$

$$C_{im} \leqslant \text{Maximum available crews} \tag{9}$$

$$C_{im} \geqslant C_i$$

Eq. (9) then becomes a more general equation for determining the modified number of crews C_{im}. In case ($Z=1$) (no risks due to site productivity loss), then ($C_{im}=C_i$), and according to Eq. (8) (CCF=1). The larger the Z factor, the more crews will result and accordingly the shorter the project duration. However, for economics, it is desired to determine the least additional crews to just meet the deadline. Therefore, it is desired to determine the minimum Z value that can compensate for the delays resulting from a certain NRS and NRE conditions.

Two steps are then needed to establish the CCF: (1) Present a mathematical representation of the crew correction factor CCF in terms of Z; and (2) establish a relationship between a given network condition (NRE, NRS) and the minimum Z factor that meets deadline, through experimental analysis. Each is discussed as follows.

1. Schedule adjustment Z as a function of crew correction factor: Representing the crew correction factor CCF by the

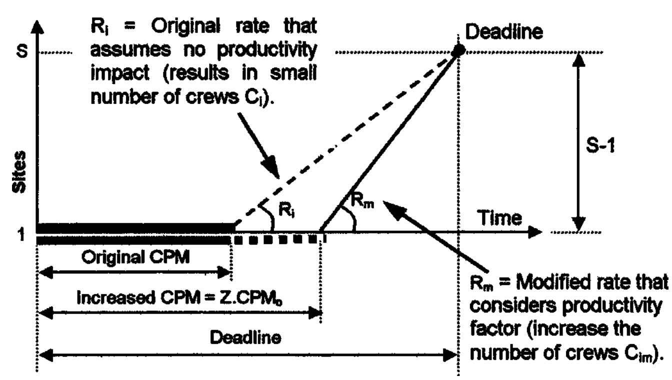

Fig. 7. Relationship between (Z) and the schedule parameter

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schedule parameter Z requires simple mathematical manipulation. First, substituting in Eq. (9) with $(Z=1)$ gives the original crews C_i for an activity:

$$C_i = d_{ik} \times \left(\frac{S-1}{\mathrm{DL} - 1 \times \mathrm{CPM}_{\mathbf{o}}} \right) \tag{10}$$

Also, From Eq. (8),

$$\mathrm{CCF} = \frac{C_{im}}{C_i} \tag{11}$$

Substituting into Eq. (11) with Eqs. (9) and (10):

$$\mathrm{CCF} = \frac{C_{im}}{C_i} = \frac{\mathrm{DL} - \mathrm{CPM}_o}{\mathrm{DL\text{-}Z} \times \mathrm{CPM}_o} \tag{12}$$

Taking

$$X = \frac{\mathrm{DL}}{\mathrm{CPM}_o} \tag{13}$$

where X=constant value indicating deadline flexibility, which is the ratio of available deadline duration to the time to finish one unit. Substituting with X, Eq. (12) is reduced to

$$\mathrm{CCF} = \frac{X-1}{X-Z} \tag{14}$$

Eq. (14) , therefore, makes the schedule multiplier Z a functional representation of the CCF factor and the constant X.

2. Schedule adjustment Z as a function of network productivity loss: To quantify the minimum Z value (representing additional crews) necessary to compensate for any network state of productivity loss (NRE, NRS), experimental results were used. To cover a wide range of possibilities, the following ranges were used:

- X: (2, 5, and 8, covering a reasonable range of CPM multiples);
- NRE: (10%, 20%, 30%, 40%, 50%, 60%, 70%, and 80%); and
- NRS: (5%, 10%, 15%, 20%, 25%, 30%, 35%, and 40%).

These, as such, are the three governing factors affecting manpower decisions in a multisite project. The X value represents deadline flexibility, while the NRE and NRS represent the network state of productivity loss. The higher the X value (i.e., farther deadline), the smaller the manpower adjustment. On the other hand, the higher the network risk, the more crews become necessary. To establish a relationship between the required Z value and the three factors above, the same 39 combinations of experiments shown in Table 2 were considered for each of the three X values (i.e., $39 \times 3 = 117$ experiments). *BAL* program was used for each of the 117 experiments to determine the smallest Z value that can overcome the project delay due to productivity loss (i.e., the minimum additional crews needed to meet deadline). In each experiment, the combination of NRE and NRS values was converted to individual site productivities then entered into *BAL* and the project delay was recorded. Different Z values were then tried (through the optimization feature of *BAL*) to recover this delay.

One example of the process to determine Z is illustrated on a 120-site project, if X has a value of 5, then the project deadline DL according to Eq. (13) is 160 days (i.e., 5×32). For the case of NRE=40% and NRS=5%, the project duration, according to *BAL*, equals 175.8 days, representing a delay of 9.9%. Trying various Z values using the optimization feature of *BAL*, the minimum value that caused the project to meet the deadline was 1.35. The results of the 117 experiments were plotted as shown in Fig. 8. The figure relates the network condition to the CPM multiplier Z needed to recover project delay. The Z factor can then be used in Eq. (14) to determine the CCF.

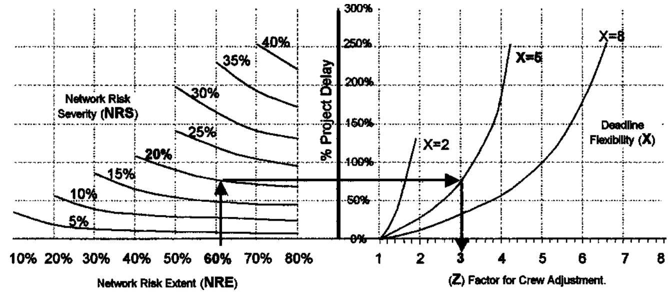

Fig. 8. Z as a function of (X, network risk extent, and network risk severity)

Manpower Adjustment Nomograph

In addition to the first nomograph which determines the basic manpower C_i, a second nomograph was developed using the nomograph drawing rules described earlier to directly determine the modified crews C_{im}. The modified crews can meet the project deadline under a given state of network risk associated with site productivity loss. To use the nomograph, the flow of arrows in Fig. 9 should be followed. The two nomographs, as such, encode all the mathematical formulations of the DSM, in addition to many scheduling and optimization experiments to meet deadline under various work conditions and wide range of sites.

Validation Example

An example construction program that involves 40 sites was used to validate the graphical approach. The graphical approach was used to determine the number of crews that correspond to a given state of network condition and the solution was checked to see if it meets the deadline duration using *BAL* program. Eleven activities are involved in a typical site. The CPM of an average site (15 days) and the logical relationships among activities are shown in Fig. 10. The construction period is from October 2nd to December 25th (approximately 60 working days). Site locations and monthly productivity factors during the construction period were assumed. Ten out of the forty sites involve low productivity, with average site productivity of 95%.

To determine the basic number of crews needed to meet the project deadline (60 days) for completing all 40 sites, the basic manpower nomograph was used with DL=60 and $\mathrm{CPM}_o=15$, for all activities. The resulting basic crews are shown in Table 3. Then, to determine the modified number of crews considering the site productivities and still meet project deadline (60 days), the network risk indicators were calculated from the given data as follows: NRE=10/40=25%; NRS=100−95=5%. Using these values with $X=\mathrm{DL}/\mathrm{CPM}_o=60/15=4$, the CCF can be determined using the crew adjustment nomograph. The basic number of crews in Table 3 is used in the nomograph of Fig. 9 to determine the modified crews. It is noted that, as a simple alternative to using the adjustment nomograph, Fig. 8 can be used with (NRE =25%, NRS=5%, and $X=4$) to determine the CPM multiplier Z as 1.4, which is then used in Eq. (14) to calculate the crew cor-

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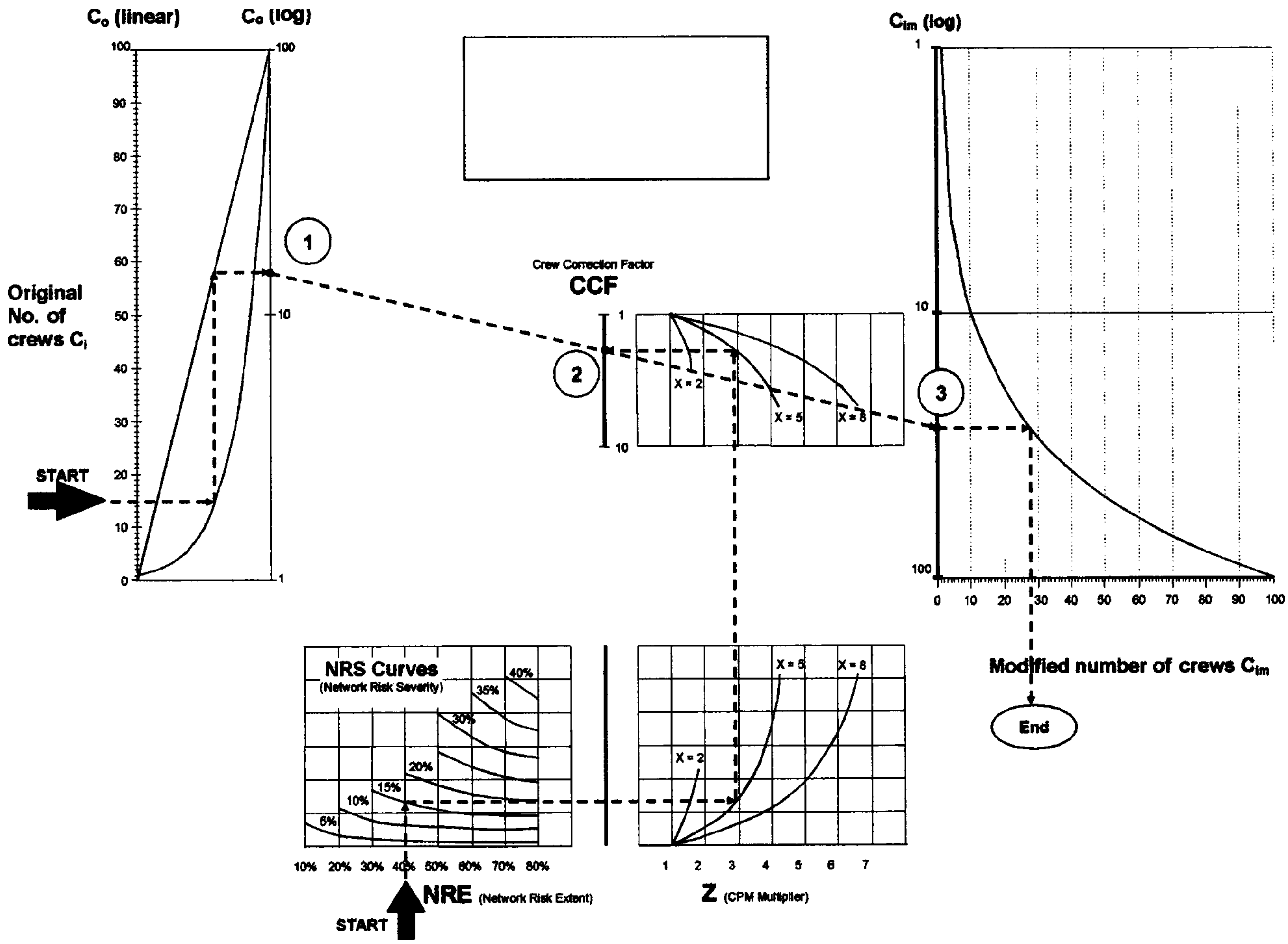

Fig. 9. Nomograph of crew adjustment

rection factor $CCF = 1.1538$, which is directly used to determine the modified number of crews.

To verify the results of the graphical solution, both the basic and the modified number of crews were entered into *BAL* program, and the project duration was determined for each case. As expected, project duration in case of basic crews was 68.9 days, i.e., involving a (14.83%) delay beyond the deadline. As opposed to that, when the modified number of crews was used, project duration met the deadline with duration of 59.6 days (Fig. 11). This demonstrates the ability of the graphical approach to estimate the necessary crews needed to meet deadline under a given number of sites and level of network risk. The small difference between the 59.6 days duration and the deadline also shows that the project meets the deadline with minimum additional manpower.

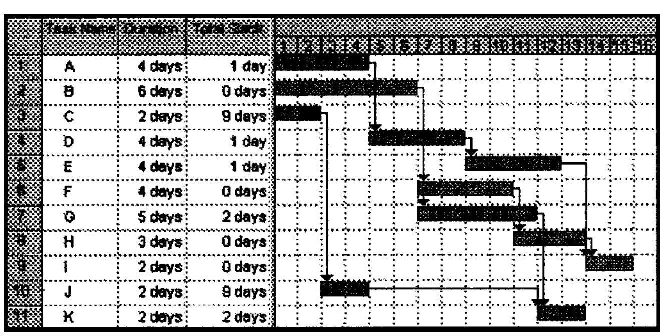

Fig. 10. Activities and logical relationships of validation example

Summary and Concluding Remarks

In this paper, two simple-to-use nomographs were developed to simplify the process of manpower planning. The first nomograph

Table 3. Basic and Modified Number of Crews

Activity	Modified crews C_{im}	Original crews C_i
Prepare site	5	4
Excavation	7	6
Compaction	3	2
Subbase	5	4
Base	5	4
Coating	5	4
Spreading	6	5
Paving	4	3
Shoulder	3	2
Marking	3	2
Testing	3	2

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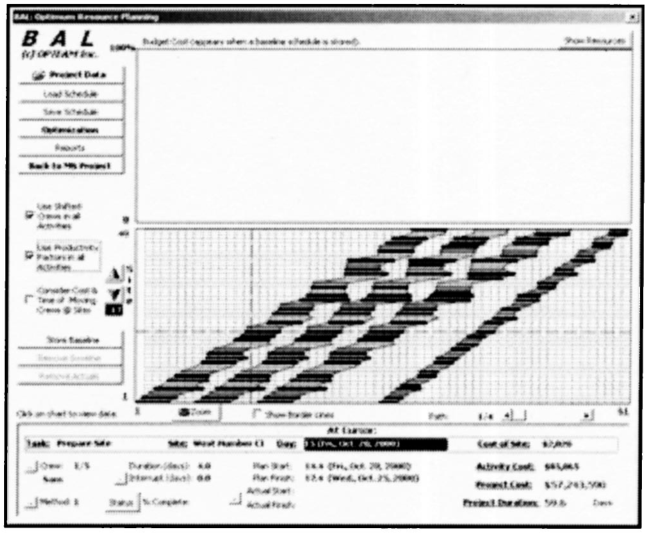

Fig. 11. Schedule using modified crews

determines the basic number of crews (manpower) needed to meet project deadline, assuming all construction sites having favorable work conditions. The second nomograph then adjusts the basic manpower needs to account for network risk, which represents the variability in work conditions among sites. The network risk is measured using two indicators: NRE and NRS. The mathematical basis for developing the nomographs are presented in the paper, followed by experimentation with the nomographs on an example to demonstrate their simplicity and practicality for manpower planning in large infrastructure networks.

The developed nomographs encode all the mathematical formulations of a distributed scheduling model, in addition to the results of many optimization experiments to meet the deadline under various work conditions and wide range of sites. Currently, program *BAL* has been used to manage maintenance programs at the Toronto District School Board, which involve hundreds of school buildings. With extensive experimentation of the nomographs and comparing with program *BAL* (computer implementation of the DSM), the nomographs provided consistent results which prove their practicality and usefulness.

The presented research represents researchers and practitioners with an effort to deal with the complex and variable nature of infrastructure networks that involve multiple sites. The nomographs have been demonstrated to be a useful tool for what-if and sensitivity analyses. They can be pulled out of the pocket of a construction manager or a municipality engineer to quickly determine the necessary corrective actions that respond to changing work conditions. This can facilitate quick decisions related to the recruitment of resources for the project, without using a sophisticated computer program. When enough time is available, a computer program such as *BAL* can then be used to decide on the specific details of crews' movements among the work site. One other possibility is to use the proposed nomographs in reverse order to estimate the project duration as a function of a given number of available crews. Detailed analysis of the use of the nomographs in a large number of owner and contractor organizations is currently ongoing and will be reported in a separate publication.

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