Computerized System for Efficient Delivery of Infrastructure Maintenance/Repair Programs

Tarek Hegazy, M.ASCE[1]

Abstract: This paper discusses three common approaches used by owner organizations to deliver infrastructure maintenance/repair (M/R) programs that involve multiple distributed sites: using in-house resources, outsourcing to contractors, and a combination of both. A scheduling model is then introduced that uses genetic algorithms to suggest the optimum combination of in-house crews and outsourcing that meet execution constraints. The scheduling model considers all the variables that relate to in-house delivery, such as available crews, methods of construction, sequence of work sites, and the time and cost of moving resources among sites. In addition, it incorporates a mechanism to examine the feasibility of replacing in-house resources by outsourcing to delegate execution risks, at minimum additional cost. Details of model development are discussed and an example application is presented to demonstrate the planning and control features of the proposed model. The model presents practitioners and researchers with a practical tool for realistic what-if assessment and greater level of control over the execution of infrastructure M/R plans.

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Introduction

In recent years, interest in developing efficient management systems for infrastructure networks, such as highways, bridges, airports, and water/sewer systems, has grown rapidly to help sustain the serviceability of the infrastructure. Existing management systems concerned mainly with developing a prioritized list of capital assets for maintenance/repair (M/R) purposes that, if executed properly, will lead to minimum life-cycle cost and maximum serviceability. With the development of the priority list, however, the majority of asset-management systems leave the delivery details to the experience of internal personnel, with little or no decision support regarding the execution sequence, resource utilization, and time/cost control (Fig. 1). This represents a major challenge that can lead to cost overruns and delays. Often, parts of one year's plan get deferred to subsequent years, and thus, the full benefit of the asset-management process, which is a costly process, does not materialize.

Planning the delivery of a large M/R program encompasses all the operational details related to the order of operations, resource assignment, outsourcing versus out-tasking contracts, schedules, and time/cost control. These, however, are very challenging tasks due to the complex nature of infrastructure M/R operations and also the stringent organizational/public/political constraints imposed at the delivery phase (Fig. 1). Common characteristics of infrastructure operations include being repetitive in nature, being scattered across distributed sites (highway spots, bridges, buildings, etc.), and requiring extensive levels of control (contracting, resource assignment, supervision, dispute resolution, cash-flow management, etc.). The larger the number of facilities involved in a new or an M/R plan, the larger the challenge. Yet, this also represents an opportunity to benefit from repetition if a crew's work is scheduled without interruption to benefit from the learning effect. On the other hand, with the scattered nature of facilities, local conditions, such as weather, by-laws, traffic congestion, etc., may vary from one site to the other. An efficient delivery (execution) plan, in this case, is one that schedules the work at each site when its productivity is highest. As such, the execution order of various sites needs to be optimally decided, considering the time and cost of transporting resources from one site to the other.

In addition to the nature of M/R operations, municipalities and asset owners strive to perform M/R operations in a timely and cost-effective manner despite various levels of constraints. At the organizational level, budgetary constraints are important to consider since they will affect the payment schedule to prospective contractors. Another important constraint on M/R execution plans is to minimize service interruption to the public and meet stringent operational requirements. Most M/R operations for municipal highway networks in Canada, for example, are carried out during the mild spring/summer season. Industrial facilities also require minimum plant shutdown during M/R. Accordingly, strict deadline duration becomes an important constraint on execution plans. To meet deadlines, speedy delivery options (often expensive) such as overtime or weekend work need to be considered.

Currently, there exist many software tools for maintenance management that either work independently or as add-on to asset-management systems. These tools provide diverse capabilities re-

[1]Assoc. Prof., Civil Engineering Dept., Univ. of Waterloo, Waterloo ON, Canada N2L 3G1. E-mail: tarek@uwaterloo.ca

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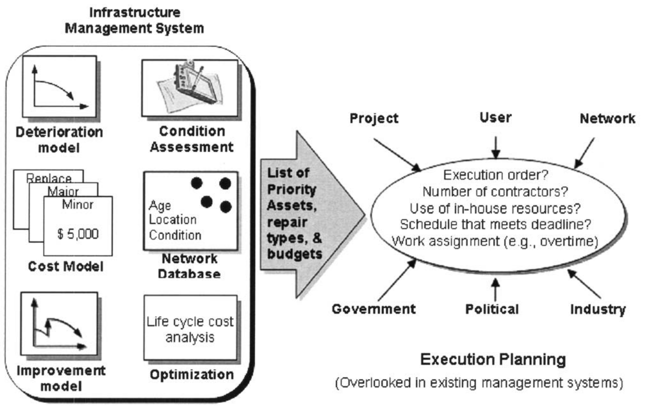

Fig. 1. Execution planning and its role in infrastructure management systems

lated to work-order tracking, resource assignment, and specialized utilities such as equipment management and materials warehousing. Some of these systems also may provide traditional planning and scheduling features. While these systems are beneficial, they address some, but not all, aspects of infrastructure execution planning. With scheduling systems using the critical path method (CPM), they inherently exhibit serious drawbacks. Despite their multiproject and resource-leveling capabilities, they are not formulated to respect a given deadline or resource limits and do not consider the distributed and repetitive nature of operations. In addition, they provide no decision support for cost optimization and do not legibly present the large amount of data involved in an M/R program with multiple sites. As such, the need has emerged for more thorough analysis of infrastructure delivery plans and for new decision-support tools that relate specifically to infrastructure networks in terms of the number of crews/contractors to use, the construction methods to employ in each activity, the varying work conditions at each site, and the site's execution order.

This paper first investigates alternative delivery approaches for M/R programs and their pros/cons. The paper then introduces a generalized model for planning and optimizing M/R programs that involve spatially distributed sites and a combination of delivery approaches. An example application is then used to illustrate implementation issues.

Delivery Methods for Maintenance/Repair Programs

In general, owner organizations adopt one of three delivery approaches to execute M/R programs: (1) using in-house resources; (2) outsourcing to contractors; and (3) a combination of both. Fig. 2 describes the types of M/R programs best suited to each approach, along with their challenges. Using in-house resources can help respond to urgent repairs. In this case, the challenge is to determine the proper number of crews to use, the work assignment option (normal work, overtime, weekends, etc.) to employ in each activity, and to optimally synchronize the schedule of crews with little interruption. Outsourcing the work at a specific site to a general contractor, on the other hand, is beneficial in passing the risks to the contractor. In this case, constraints related to available experienced contractors, time for bidding and contractor selection, and cash-flow requirements should be considered. When using a combination of in-house crews and contractors, the challenge becomes larger and both types of constraints need to be taken into account. In addition to these three delivery options, it is possible for an owner organization to hire a subcontractor to handle one specific aspect of a certain site (e.g., concreting only). In this case (often referred to as out-tasking), the majority of the work at the site is delivered by in-house resources, except for the out-tasked activity.

In the past decade, many public and owner organizations have resorted to outsourcing, coupled with downsizing of in-house construction departments, as a cost-saving strategy. This approach has been successful for small and medium-sized organizations that can manage all M/R operations through outsourcing. Recently, however, large organizations that have diverse M/R programs have resorted to in-house delivery in addition to outsourcing. A positive experience by one owner organization, the Toronto District School Board (TDSB), has reported a successful strategy of delivering part of its infrastructure M/R programs utilizing

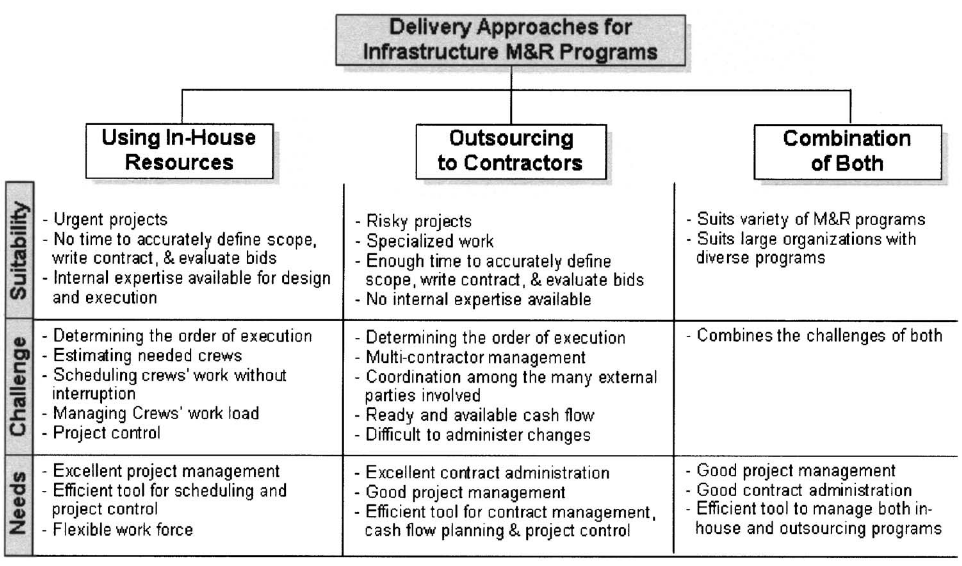

Fig. 2. Delivery approaches for M/R programs

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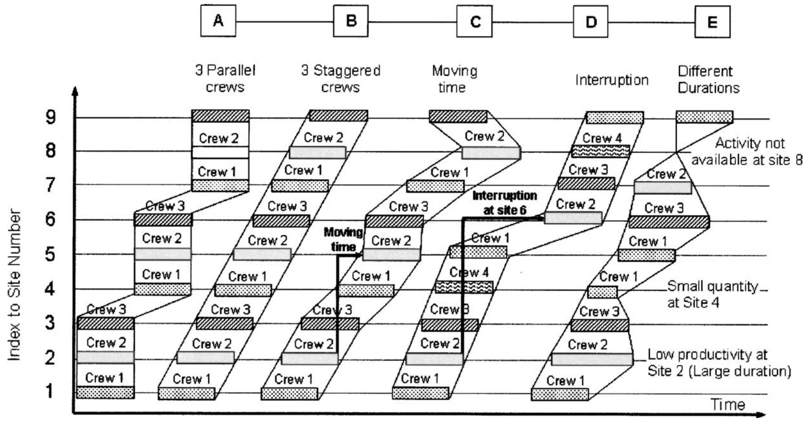

Fig. 3. Scheduling of crews along multiple sites

in-house crews (Attalla and Hegazy 2001). The TDSB, which is one of the largest school boards in North America, owns about 660 school and administrative buildings. It administers 50 million-dollar annual M/R programs that have to be completed during the short summer period before schools are open. The number of sites that have to be maintained can be as large as 200 sites in parallel (e.g., window replacement or roof replacement programs). After downsizing, restructuring, and amalgamation, the TDSB was able to identify that the candidate programs for in-house delivery are the ones that are highly urgent, have inadequate scope definition, and can be executed with in-house expertise. According to the TDSB experience, many factors contribute to the success of in-house projects, including partnership with trade unions, benchmarking, standardization of procedures, resource planning, flexible work force, effective organizational structure, timely material procurement, efficient scheduling and control, detailed health and safety management, quality control, and communication management.

Planning the Delivery of Maintenance/Repair Programs

As compared with traditional projects, planning the M/R 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.

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, specifically using in-house resources. A brief description of the DSM model and details of its extension to the more general case of combined delivery approaches are presented in the next sections.

Using In-House Resources

The DSM (Hegazy et al. 2004) is a resource-driven model that determines the optimum amount of in-house resources to be employed in any M/R program involving multiple distributed sites that have different work conditions and work quantities. The main features of the 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 up to three work methods for each activity, varying from cheap and slow to fast and expensive (e.g., normal work, overtime, or subcontractor); each activity method has specific resources, duration, and cost;
4. Allows activities to be defined once for all the repetitive sites, yet allows nonstandard sites to have varying quantities of work;
5. Has detailed formulation to calculate the necessary number crews for each activity that meet the deadline, under favorable work conditions at various sites; and
6. Incorporates an algorithm for optimizing the delivery plan under any set of site conditions. The algorithm determines the best execution sequence among the sites, and the best activities' crews and work options so that total cost is minimized.

In the basic DSM, the duration d_{ijk} of activity i, which uses construction method j in site k, is calculated as

$$d_{ijk} = \frac{Q_{ijk}}{P_{ijk} \times f_{kL}} \tag{1}$$

Where, Q_{ijk}=quantity of work; P_{ijk} 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,…, 12) in which the activity is scheduled. Then, the critical path duration of a typical site is calculated as CPM_o, and the total float value TF_i for each activity i is accordingly calculated. Afterward, the crews C_i needed for each activity to meet a deadline duration DL for completing an M/R program involving S sites, under favorable work conditions, is determined as (Hegazy et al. 2004)

$$C_i = \text{RoundUp}\left\{ d_{ik} \times \left(\frac{S-1}{DL - CPM_o + TF_i} \right) \right\} \tag{2}$$

$$C_i \leq \text{Maximum available crews}$$

Once the activities' crews are calculated from Eq. (2), they can be scheduled along the various sites in many ways, as shown in Fig. 3. The figure shows a legible schedule of the large amount of data in an M/R program, with time on the horizontal axis and site index on the vertical. The schedule shows five sequential activities in nine sites. The schedule illustrates various features: color-coded or pattern-coded crews; crew moving time; varying quantities; site-condition impact; crew interruption time; crew staggering; crew work sequence; and relative speeds of activities

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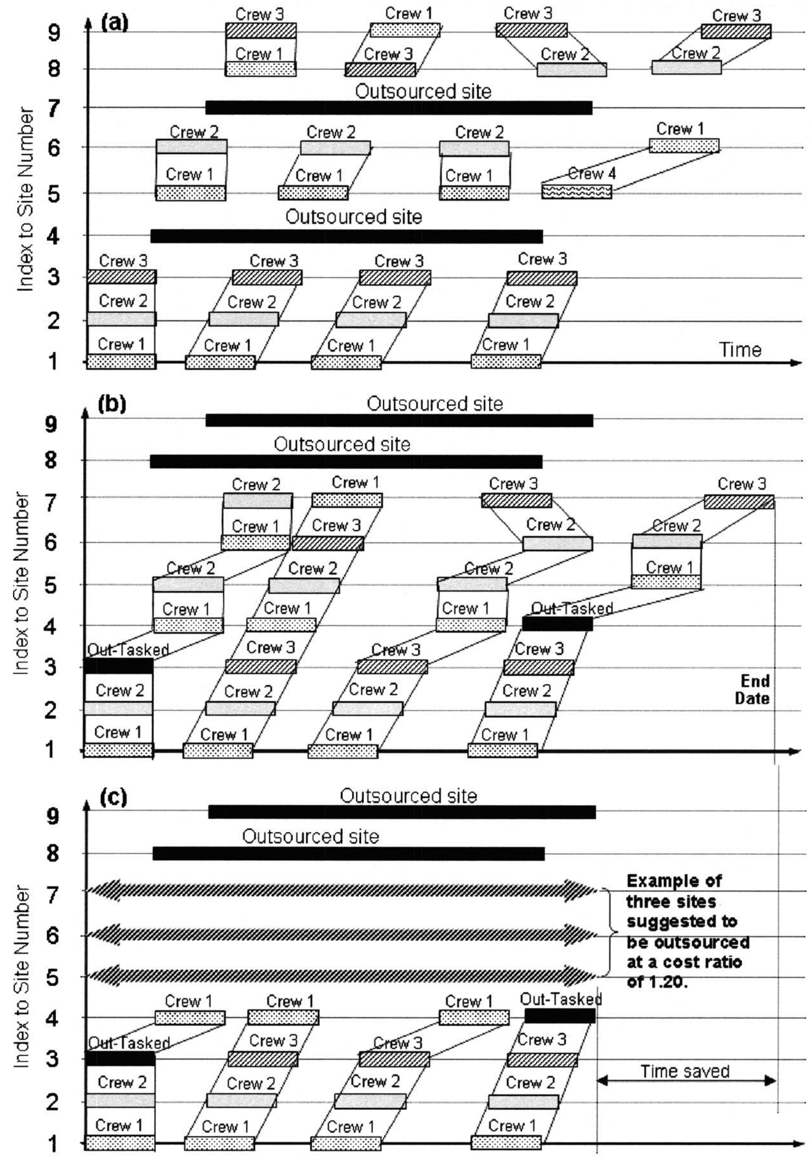

Fig. 4. Scheduling of outsourced sites: (a) according to site sequence; (b) sorted separately at top; (c) sample result of the outsourcing-feasibility algorithm

(slopes of lines). In the case when site conditions are expected to delay the project beyond its deadline, the optimization algorithm can be applied to select more speedy options for some of the activities to minimize total cost. It is noted that in Fig. 3, all crews are scheduled so that they move from one site to another, without interruption, to improve productivity.

Using In-House Crews, Outsourcing, and Out-Tasking

As explained, the DSM helps in scheduling multisite M/R programs that are delivered using only in-house resources that are part of the planner's work force. Generalizing the DSM to any combination of delivery methods requires adjustments related to data management, crew calculations, scheduling, and optimization.

Assume, for example, that two out of the nine sites of Fig. 3 will be outsourced to contractors to relieve in-house crews or to pass risky jobs to experienced contractors. In Fig. 4(a), sites 4 and 7 are shown as solid bars that represent the contractual periods for the two sites. It is noted, however, that the representation in Fig. 4(a) shows discontinuity in the schedule, which does not suit project control purposes, particularly when the number of sites is much larger. A simple but effective modification, therefore, is to sort all the outsourced sites at the top of the schedule, as shown in Fig. 4(b). In this manner, the schedule for the in-house crews remains continuous and gives useful information about crews' movements and speed of progress. It is also possible to apply an out-tasking strategy to subcontract the work of any activity at any site. In this case, the in-house crews will be relieved from this work. Two examples of out-tasking are shown in Fig. 4(b) for the first and the last activities. For the first activity, three crews were scheduled, as shown in Fig. 4(a), but when the work of the third crew is out-tasked at site 3, only two crews are needed to complete the work. Similarly, one crew is saved when the last activity is out-tasked at site 4. It is noted that out-tasked activities are represented by a different pattern or color for clarity. Based on this discussion, outsourced sites require scheduling and represen-

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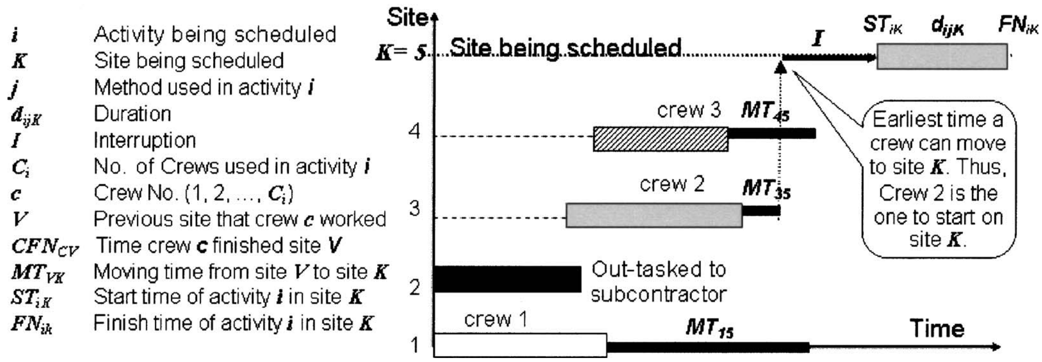

Fig. 5. Calculating start and finish times

tation of their contract information such as start time, duration, and contract value. For project-control purposes, on the other hand, the actual start time and the percentage complete will be needed to represent outsourcing progress.

Outsourcing-Feasibility Algorithm

Different owner organizations use varying combinations of in-house crews and outsourcing. This varies from total dependence on in-house crews to full downsizing and dependence on outsourcing. To support the wide spectrum of organizations, a new module has been added as part of the DSM to assess the sufficiency of existing in-house crews to deliver M/R plans and, if not, support the decision of which sites are best delivered through outsourcing, considering the cost and time implications. This outsourcing-feasibility algorithm assumes the cost of an outsourced site to be a proportion of the typical in-house delivery cost. Based on a user input of this cost ratio (e.g., 1.20 if outsourcing is 20% more costly than in-house delivery), the cost implication can be determined.

To illustrate the algorithm, assume that a preliminary schedule such as that of Fig. 4(b) is available. The top two outsourced sites are fixed as the contracts are set for them. Accordingly, the finish time of the whole program reflects the number of crews and the site execution order. The end date, as shown, is that of site 7 and is governed by the crews used. As such, if a shorter completion date is needed, it is possible to suggest an outsourcing strategy for site 7 (largest site order with in-house crews). This relieves in-house crews and passes the risk of a shorter deadline to contractors. However, a trade-off has to be considered in case outsourcing is very expensive (i.e., when the outsourcing cost ratio is higher than the savings in liquidated damages and indirect cost).

Based on the above discussion, the outsourcing-feasibility algorithm was developed to examine the cost and time implications of outsourcing. The algorithm checks all the sites that use in-house crews one by one, from top to bottom—that is, site 7, then site 6, etc., through to site 1. For each site, in-house crews are replaced by a suggested outsourcing strategy. Accordingly, total execution time and cost are calculated, considering the pre-specified outsourcing cost ratio. If total cost is reduced (i.e., savings in liquidated damages and indirect costs are higher than the additional outsourcing cost), the process continues to the next site until it reaches a site at which no cost improvement is made. A sample result of the algorithm is schematically illustrated in Fig. 4(c). The algorithm, as such, can suggest whether an outsourcing strategy is advantageous under any user input value of the outsourcing cost ratio. It is noted that if the original schedule [Fig. 4(b)] meets a given deadline, then the algorithm will not suggest any additional sites for outsourcing, as this will bring extra cost to the project. On the other hand, if the deadline is very restrictive, then the algorithm will suggest the least amount of outsourcing (i.e., least additional cost) to meet a given deadline.

Schedule Calculations

In the generalized DSM algorithm, the sites are assigned to the crews, not the opposite. In this approach, a site is assigned to the first crew that becomes available for work. As shown in Fig. 5, crew 2 proceeds to site 5, immediately after it finishes site 1, because other crews are still busy in other sites. During the process, crew movement time and cost among sites are considered. Accordingly, start (ST_{ik}) and finish (FN_{ik}) times of each activity i at every site k are calculated as follows (notations shown on Fig. 5)

$$ST_{iK} = \min(CFN_{CV} + MT_{VK})_I^{Ci} + I \geqslant \text{Finish time of predecessors} \tag{3}$$

$$FN_{iK} = ST_{iK} + d_{ijK} \tag{4}$$

where d_{ijK}=work duration at site K, calculated using Eq. (1), considering productivity factors. It is noted that the calculations skip the sites that are being out-tasked (e.g., site 2 in Fig. 5). Also, as shown in the figure, crew 2 is the one to move to site K. If the finish time FN_{ik} of this site is beyond a given deadline, then changes to the schedule need to be made. One option is to out-task this site to a subcontractor.

Cost Optimization

The generalized DSM model is capable of generating schedules by manually changing the options for construction methods, number of crews, the site order, and the amount of interruption at various sites. Then, under any predetermined set of values for these variables, the outsourcing-feasibility algorithm can suggest the sites to be outsourced to improve total execution time and cost. However, with the large number of possibilities, even for a small network of sites, a cost optimization model becomes necessary to identify the optimum combination of these variables to meet all the schedule constraints. The optimization model involves the setup of the objective function, optimization variables, and optimization constraints. To incorporate the outsourcing-feasibility algorithm, the original optimization algorithm of (Hegazy et al. 2004) has been extensively modified.

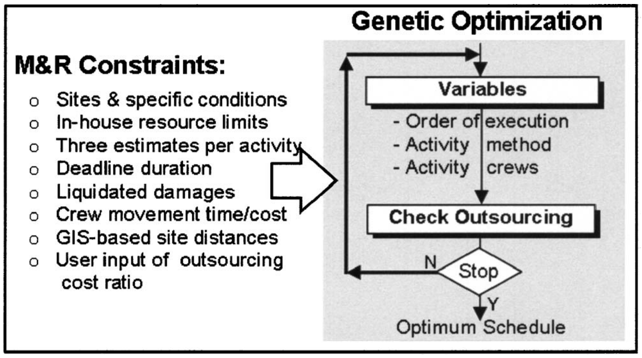

Fig. 6. Developed program

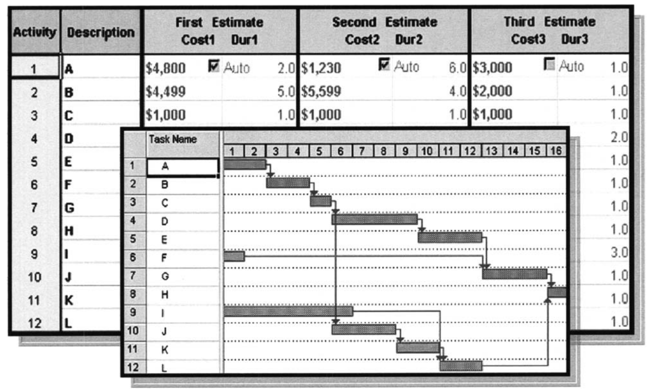

Fig. 8. Optional estimates and logical relationships

The objective function of the model is to minimize total construction cost, encompassing: (1) direct cost; (2) indirect cost; (3) liquidated damages; (4) incentive for early completion; and (5) crew moving cost. With the large number of variables involved, the solution space can be extremely large and thus genetic algorithms (GA) provide a major advantage over mathematical optimization in finding a solution. Along with proper ranges for the variables, two soft constraints are used: (1) project duration should be less than or equal to the deadline duration; and (2) total aggregated amount of a given resource is less than or equal to the amount available. For flexibility, and to reflect the project manager's objective, all variables and scheduling options such as considering crew moving time/cost or site productivity factors can be set to on/off during the optimization.

Since the GA process works by randomly generating and examining many sets of values for the variables, the outsourcing-feasibility algorithm has been set up to be activated for each set of values. As such, outsourcing of sites becomes one of the optimization variables and the final solution of the process provides a suggestion for the least costly combination of in-house resources and outsourcing.

Implementation

A computer software program of the generalized DSM was developed using visual basic programing language. A schematic diagram of the software is shown in Fig. 6. To consider the time and cost of moving crews among sites, the program uses a simple geographic information system (GIS) that automatically calculates the distances among sites.

Site	Street	Jan	Feb	Ma	Ap	Ma	Jun	Jul
North York Oakburn Ce	15 Oakburn Crescent	0.7	0.7	0.8	0.8	0.9	1.0	1.0
Blaydon PS	25 Blaydon Ave.	0.7	0.7	0.8	0.8	0.9	1.0	1.0
Stanley PS	75 Stanley Rd.	0.7	0.7	0.8	0.8	0.9	1.0	1.0
Stilecroft PS	50 Stilecroft Dr.	0.7	0.7	0.8	0.8	0.9	1.0	1.0
Ledbury Park E & MS	95 Falkirk Street	0.7	0.7	0.8	0.8	0.9	1.0	1.0
Arbor Glen PS	55 Freshmeadow Dr.	0.7	0.7	0.8	0.8	0.9	1.0	1.0
Gateway PS	55 Gateway Boulevard	0.7	0.7	0.8	0.8	0.9	1.0	1.0
Leaside HS	200 Hanna Ave,	0.7	0.7	0.8	0.8	0.9	1.0	1.0
Etobicoke CI	Broadway Ave	0.7	0.7	0.8	0.8	0.9	1.0	1.0

Fig. 7. Site locations and productivity factors

Example Application

To illustrate the features of the developed computer program, a simple example of an M/R program is presented. The program resembles a municipality having nine sites (buildings, highway spots, bridges, etc.) with varying conditions and work quantities. First, the sites were defined, as shown in Fig. 7, by their address (recognizable by the GIS software). For each site, the user enters the local productivity factors (monthly values that depend on weather, site access, and other conditions). Using these productivity factors (e.g., February and March factors are 0.7 and 0.8, respectively), task durations are adjusted during the scheduling process, thus providing realistic execution conditions.

The twelve activities involved in a typical site along with their logical relations were then defined, as shown in Fig. 8. The work quantities and three estimates that represent normal, overtime, or weekend work options are shown in the same figure. While the cheaper estimate is the default in generating an initial work plan, the other options (faster but more expensive) may be necessary in case durations need to be shortened to meet a strict deadline. In this case, finding the proper combinations of work options for the activities becomes part of the optimization feature.

Before producing a detailed schedule, the user needs to enter some general data such as start date (Feb. 11, 2003, as shown in Fig. 9) and the execution constraints such as deadline (March 12, 2003), incentive ($10,000/day), liquidated damages ($100,000), and any resource limits. As such, this example M/R program has only 22 working days (after excluding weekends) to complete the nine sites.

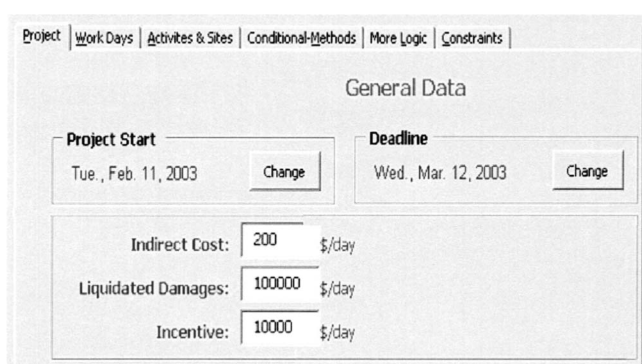

Fig. 9. Main input screen with general data

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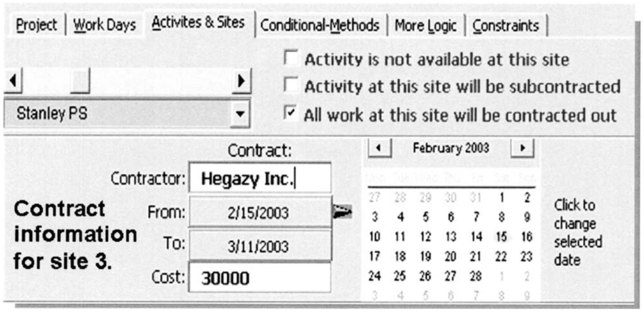

Fig. 10. Delivery options at each site

With the default option being to use in-house crews, the next step was to enter information regarding any special sites that were decided to be outsourced to contractors. In this example, two of the nine sites were prespecified as outsourced. An example of the data entry is shown in Fig. 10, where site 3 (according to order of user entry) was specified to be outsourced from Feb. 15, 2003, to March 11, 2003, for $30,000 (an outsourcing cost ratio can be readily calculated). After specifying these options, a detailed execution schedule can be generated.

The initial schedule produced by the program is shown in Fig. 11, showing the various color-coded crews. The two contracted sites are shown at the top part of the plan. It is noted that the initial site order is the one entered by the user in Fig. 7. Based on that site order, project duration and cost (considering crew-moving time and cost) were automatically calculated, taking into account the site productivities. This resulted in a schedule of 26 days, as opposed to the 22-day deadline. Accordingly, the cost becomes $283,882, plus liquidated damages of $400,000, for a total of $683,882.

To improve the schedule, it is possible to manually change the crews, work options, and site order to try to meet the deadline and reduce cost (user modifiable options are shown in Fig. 11). It is also possible to activate the outsourcing-feasibility algorithm from the option shown in Fig. 11. Upon user input of a cost ratio, the suggested sites for outsourcing will be highlighted. Rather than this manual adjustment process, it is possible to activate the optimization feature, and accordingly, a form for specifying optimization options appears (Fig. 12), allowing the user full control over the optimization variables, including outsourcing, to suit the project objectives. For this example, various optimization experiments were conducted with and without outsourcing. Two sample optimum schedules are shown in Fig. 12. The top schedule does not involve outsourcing; project duration of 21 days meets the deadline at a total project cost of $334,299. With outsourcing, various values for the outsourcing cost ratio were used in various experiments. The bottom schedule in Fig. 12 shows the results when a 1.40 cost ratio is used. The resulting schedule shows that five additional sites are suggested for outsourcing, while in-house crews would be involved in the bottom two sites only. As such, the model is capable of suggesting the location and frequency of outsourcing to meet the deadline with minimum cost ($329,271). Conducting various optimization experiments, it was found that for this example, using any cost ratio higher than 1.40, outsourcing becomes very expensive and no sites were suggested for outsourcing. It is noted that while the total cost of outsourcing is smaller than the case of no outsourcing, the schedule becomes feasible only if contractor bids for the outsourced sites are expected to be no more than 40% higher than in-house costs (since

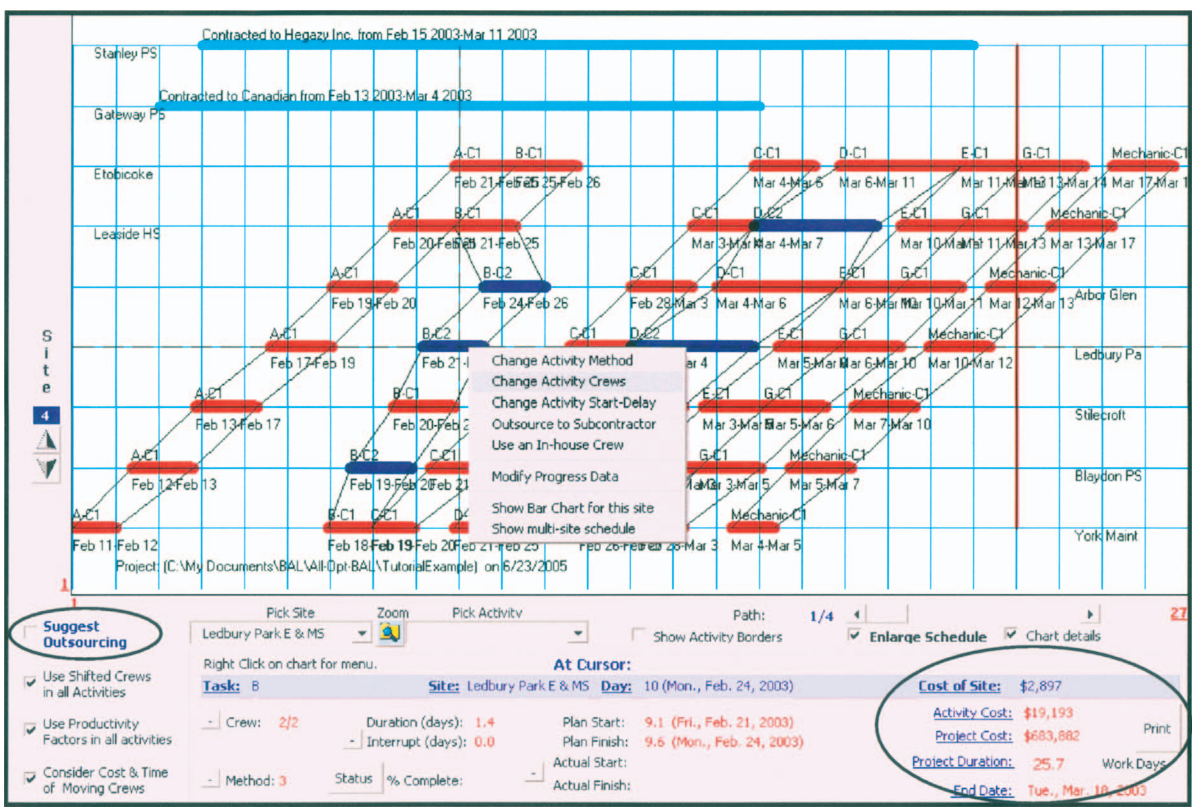

Fig. 11. (Color) Initial schedule

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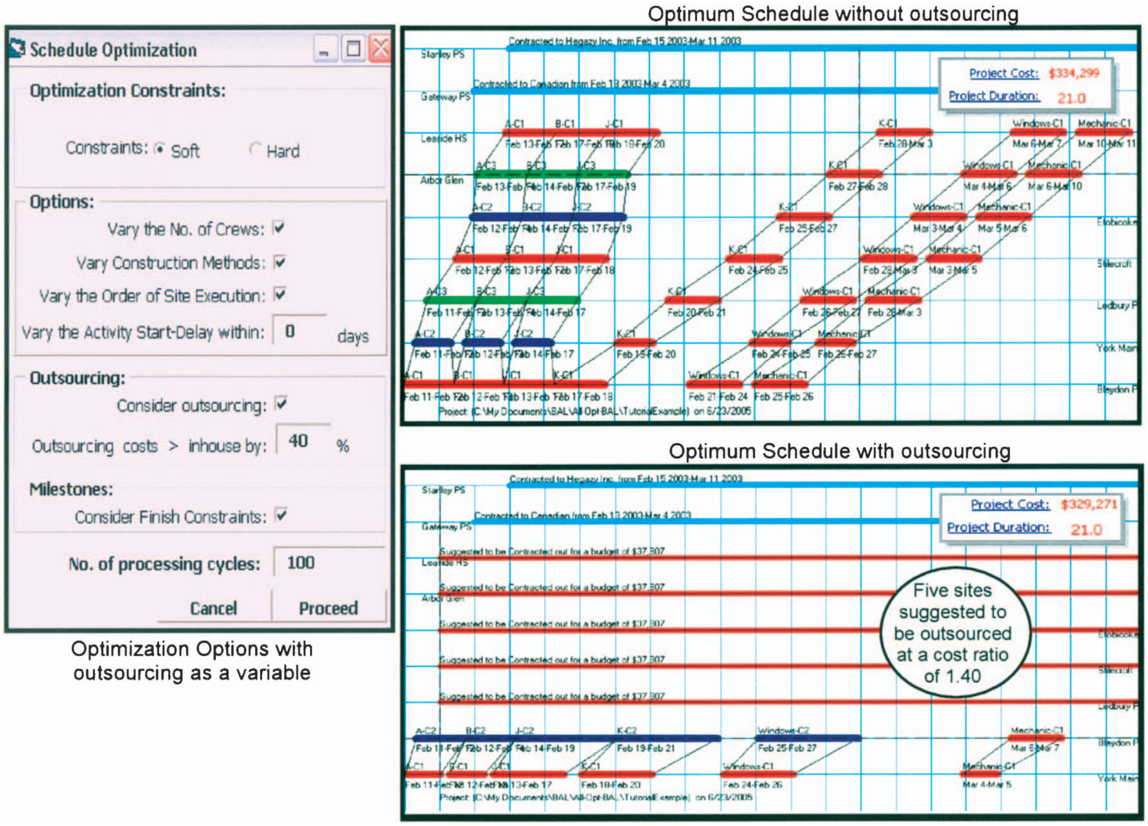

Fig. 12. (Color) Schedule optimization

the optimum schedule was developed using a 1.40 cost ratio). In this example, it is assumed that the schedule with no additional outsourcing is preferred (to be able to demonstrate the out-tasking feature discussed later).

Once a satisfactory schedule was arrived at, it was saved as a baseline for progress control. For project-control purposes, the program allows the user to enter actual progress information (Fig. 13) and the schedule is automatically adjusted accordingly. For demonstration purposes, one activity is specified to be executed. As shown in Fig. 13, on Feb. 14, 2003, the activity was 10% complete, carried out by crew 2, and actual cost was $1,000. Once this information was input, the whole schedule was automatically adjusted and project duration was projected to be 28 days. It is noted that the program moves the site(s) with actual progress information to the bottom, which is a useful feature to sort and draw the started sites according to their actual start dates. Also, the work in progress is given a different color for clarity.

Due to the late start in executing the plan, corrective actions were needed to bring the project within its constraints. For that purpose, the optimization feature can be reactivated and the crews, work assignment options, and site order associated with the remaining part of the schedule can be reoptimized to dynami-

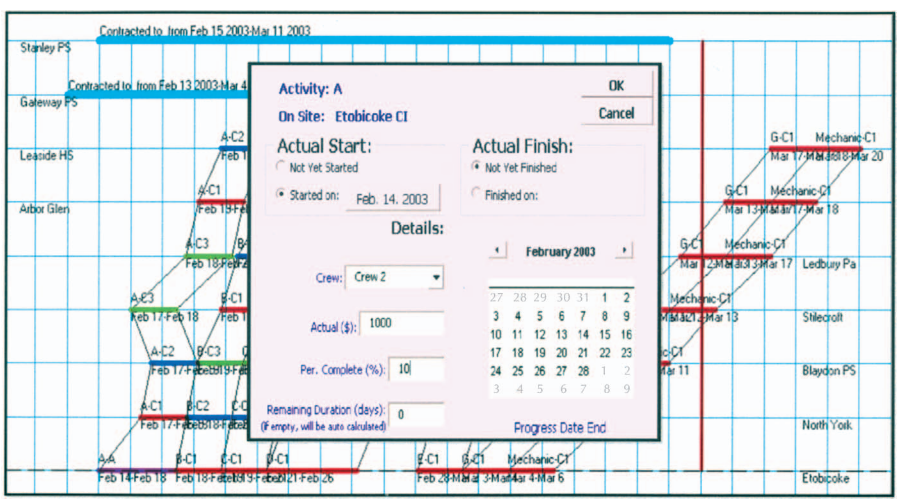

Fig. 13. (Color) Schedule with progress delay

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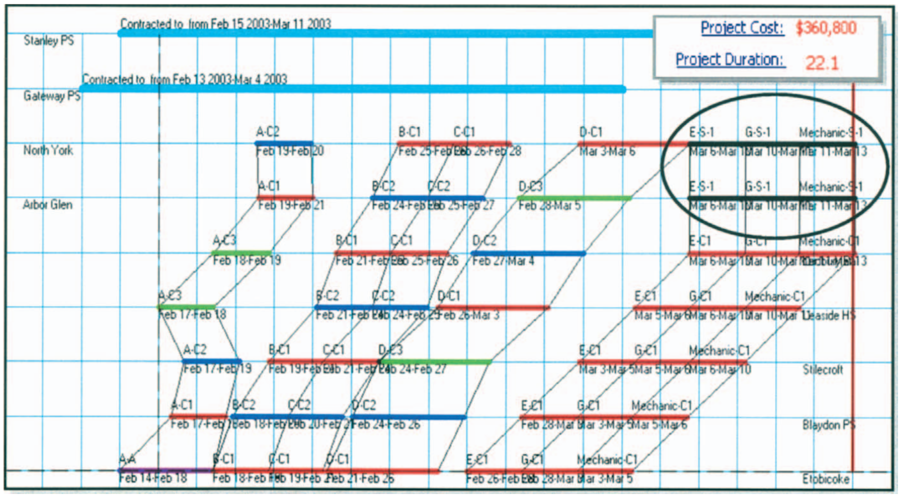

Fig. 14. (Color) Reoptimized schedule

cally meet project constraints at minimum cost. After activating the optimization feature, it was clear that the deadline was very difficult to achieve with the number of in-house crews available.

To save some time, parts of the activities in some sites had to be out-tasked to subcontractors, as shown in the circled part of Fig. 14. Accordingly, a 22-day duration was obtained at a cost of \$360,800. As such, the various delivery approaches used in the program proved to be very beneficial. Not only does the program instantaneously show the results of all progress events on site (a useful what-if feature), but it also has the ability to come up with optimized corrective actions. Additionally, to facilitate project control decisions, detailed earned-value charts were incorporated into the program.

One of the main benefits of the proposed model and its implementation is the legible schedule representation of the large amount of data related to multiple sites and various delivery details. While the presented example is simplistic and involves only nine sites, the program was used on example M/R programs involving hundreds of sites. Based on extensive experimentation, the GA-based optimization algorithm performs consistently and provides near-optimum solutions to execution plans. With respect to its use on real-life projects, an earlier version of program (which does not include the various delivery methods) is currently being successfully used at the TDSB to manage their in-house resources involved in large M/R programs such as window/roof replacement, which involve more than 100 schools (Attalla 2003). Continued experimentation is currently being carried out to experiment with the program on a combination of delivery approaches in real infrastructure networks.

Summary and Concluding Remarks

While infrastructure asset-management systems are concerned mainly with prioritizing assets for repair purposes, execution planning has been presented in this paper as an important supplementary dimension that is necessary to achieve the desired benefits. To support organizations in this difficult task, a scheduling model has been introduced and its use on an example application presented. The model and its optimization feature is unique in its ability to consider outsourcing as an optimization variable to determine the most cost-effective delivery plan for infrastructure M/R programs. As such, the model is able to not only optimize the site order, construction methods, and use in-house crews, but also to suggest the location and frequency of outsourcing necessary to minimize the cost of delivery. The model and its implementation program are potentially usable by municipalities and owner/contractor organizations administering a large number of infrastructure assets.

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