Genetic Optimization for Dynamic Project Control

Tarek Hegazy, M.ASCE,[1] and Kevin Petzold[2]

Abstract: This paper presents a comprehensive model for cost optimization and dynamic project control. The model incorporates an integrated formulation for estimating, scheduling, resource management, and cash-flow analysis. The basic premise of the model is to allocate optional construction methods for each activity, varying from cheap and lengthy to expensive and short. Using a genetic algorithms procedure for total cost optimization, the model considers the actual progress of activities and optimizes the schedule of remaining ones (by determining the best combination of construction methods) so that project constraints are respected. The model, as such, is usable not only at the planning stage but also during construction. A description of the model and its application on an example project are provided in this paper. In addition, the paper introduces the recently emerged critical chain method for project control and describes an effort to incorporate some of its features into the earned-value analysis used in the proposed model.

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Introduction

Project monitoring and control are necessary to measure the deviation of actual from planned progress so that corrective actions can be made to meet project budget and deadline. While various project management tools are available commercially, their role has focused mainly on developing usable plans before start of construction but do not optimize such plans in response to actual progress challenges.

This research presents a practical model for determining optimized corrective actions during the execution of construction projects, considering time, cost, and resource constraints, concurrently. It extends the capabilities of a spreadsheet model originally designed for project planning to include project tracking, progress reporting, and corrective action optimization using genetic algorithms. An effort is also made to combine the benefits of traditional project control techniques with those of the newly emerging method, critical chain project management (CCPM), to provide a general framework for project control that incorporates the proposed model.

Previous Efforts on Overall Plan Optimization

The difficulties associated with managing the time, cost, and resources in construction projects have been acknowledged over the years and various techniques have been developed to address these aspects individually. Techniques such as time-cost tradeoff (TCT) analysis, limited resource allocation (resource scheduling), and resource leveling have been in practice since the 1960s. These techniques, however, are applied to projects one after the other, thus producing less than optimum schedules. This is as a result of the complex nature of projects, the difficulty of modeling all aspects combined, and the inability of traditional optimization tools to solve large-scale problems.

Among the limited efforts that focused on overall schedule optimization is the integer-linear programming model of Karshanas and Haber (1990). The model minimizes the total project cost, considering resource constraints, time (represented as cost), and monthly cash flow limit. Li (1996), also developed a mathematical programming model that performs overall schedule optimization considering investment allocations, resource supply, and weather impact on productivity. In both studies, however, the researchers reported that the models were suitable only for projects with very limited number of activities due to the complexity of model formulation and the limitations that plague mathematical optimization.

Motivated by the rapid growth of computer technology and the recent developments in artificial intelligence, nontraditional models have been proposed to solve complex civil engineering and construction management challenges. Genetic algorithms (GAs) have emerged as a promising optimization tool in construction management application, and as such, have been employed in several applications including: bidding strategy (Hegazy and Moselhi 1994); resource scheduling (Chan et al. 1996); and TCT analysis (Li and Love 1997). Hegazy (2002) developed an optimization model in a spreadsheet application that considers cash flow management, TCT analysis, resource allocation, and resource leveling, simultaneously. The model employed GAs to optimize the schedule at the planning stage. This work is extended in this paper to optimize corrective actions throughout the construction phase.

Project Control Techniques

Based on the critical path method (CPM), the earned value procedure discussed by McConnell (1985) is a quantitative method

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

[2]Graduate Student, Civil Engineering Dept., Univ. of Waterloo, Waterloo ON, Canada N2L 3G1. E-mail: kkpetzol@engmail.uwaterloo.ca

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Table 1. Critical Chain Concept

Planning phase	Control phase
Estimating with safety removed (50% probability)	Focus on finish time of predecessors
Planning backwards to focus on deadline	
Scheduling as late as possible to improve financing	Buffer management
Resolving resource conflicts	Staggering multiprojects
Identifying the critical chain	
Inserting project buffer at end of project (50% of CPM)	
Inserting feeding buffers to protect the critical chain	

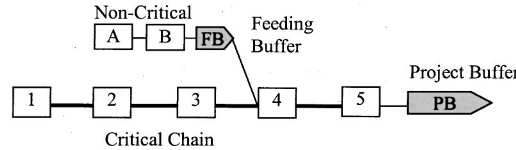

Fig. 1. Insertion of feeding buffer and project buffer

widely accepted for project cost and schedule control. The effective execution of the earned value technique, however, hinges on the accuracy of project planning. To improve project control based on earned value, various researchers have focused on automating various aspects related to accurate real-time evaluation of project performance and identification of potential problems. Rasdorf and Herbert (1990), for example, used bar coding to control data acquisition needs for construction. Lin and Tserng (2001) introduced a communication mechanism to automate data transfer for construction schedule control using XML-based information.

In a different approach, Russell et al. (1997) used a database of historical S curves for successful and less-than-successful projects as benchmarks against which new projects can be compared. Other nontraditional methods for project control include the work of Karim and Adeli (1999) using an object-oriented information model for construction scheduling, cost optimization, and change order management. It provides an intelligent decision support system for schedule reviews, progress monitoring, TCT analysis, and change order approval. Based on the above literature, earned value is a beneficial tool for identifying project cost and time variances. Earned value, however, does not recommend any strategies to minimize the expected losses due to the variances. This is where the present paper attempts to improve by determining the optimal corrective actions during construction.

New Concept for Project Control: Critical Chain Project Management

Recently, a radically different approach to project control, CCPM was introduced by Goldratt (1997). This technique responds to some of the drawbacks of traditional project control, including: estimating activity duration with excessive safety factors; tendency to start late on activities (student syndrome) as a result of the false feeling of security; workers adjustment of their effort to keep busy for the entire task duration (Parkinson's law); project managers stressing not being late but benefiting from early finishes; and the delays caused by moving resources among multiprojects.

To address these issues, the CCPM applies an interesting approach during the planning and control phases of projects (Table 1). It removes the hidden safety in the task durations and later replaces them by buffers at key points in the project plan to act as shock absorbers against delays. The goal is to get a task estimate that has a 50% probability of being met. Project planning then proceeds backward in time from a target end date, placing the focus on the completion date. All tasks are scheduled as-late-as-possible, as opposed to the as-soon-as-possible approach of CPM, from the target end date so that costs are not incurred earlier than necessary. One of the obvious drawbacks, however, is that all tasks become critical. To circumvent that, buffers will be inserted at key locations in the project plan. During the scheduling process, traditional heuristic resource scheduling techniques can be used to resolve resource overallocations.

The critical chain (the longest chain of tasks that consider both task dependencies and resource dependencies) is then identified and two types of buffer zones are inserted to compensate for the removed safety: project buffer and feeding buffer (Fig. 1). The project buffer is placed at the end of the project to protect against exceeding the target deadline. Usually project buffer is set as 50% of the length of the critical chain. The feeding buffer, on the other hand, is needed at the intersection between any noncritical chain and the critical chain. This protects the critical chain against overruns on other chains. The size of the feeding buffer is 50% of the length of its noncritical chain.

During construction, the CCPM uses a relay race approach that de-emphasizes the exact start and finish dates of tasks and concentrates, instead, on starting each task as soon as its predecessors are completed. In this manner, it capitalizes on the early finishes of preceding tasks. As opposed to the CPM approach however, the CCPM does not apply any project control technique such as earned value and is not concerned when a particular task overruns its estimate. Instead, the concept simply watches the buffers and monitors how much of it is penetrated by schedule changes. The buffer is divided into three equally sized regions: green, yellow, and red, to signal no action, warning sign, and corrective action, respectively. In the critical chain concept, a new project is also scheduled in a manner that avoids overlapping and multitasking with other projects to avoid conflict with key resources. This staggering of projects acts as a protection against delay due to limited availability of a key resource. Despite some controversy regarding the critical chain, it provides interesting features that can be utilized to improve traditional project control without much impact on current processes (Leach 1999).

Proposed Model: Resources, Estimate, and Schedule

The proposed model is designed to store resource data and use it to perform estimating, scheduling, control, and dynamic optimization. A schematic diagram of model components is shown in Fig. 2. The model is developed as a spreadsheet template that incorporates all functions in a user-friendly interface that hides all complexities. A professional version of the program (copyrighted to the first author) is used to demonstrate the model. In this section, the resource depository, estimating, and scheduling functions are explained while project control and dynamic optimization are explained in separate sections. To clearly describe the model, a hypothetical example, adapted from Hegazy (2002), is used (Fig. 3).

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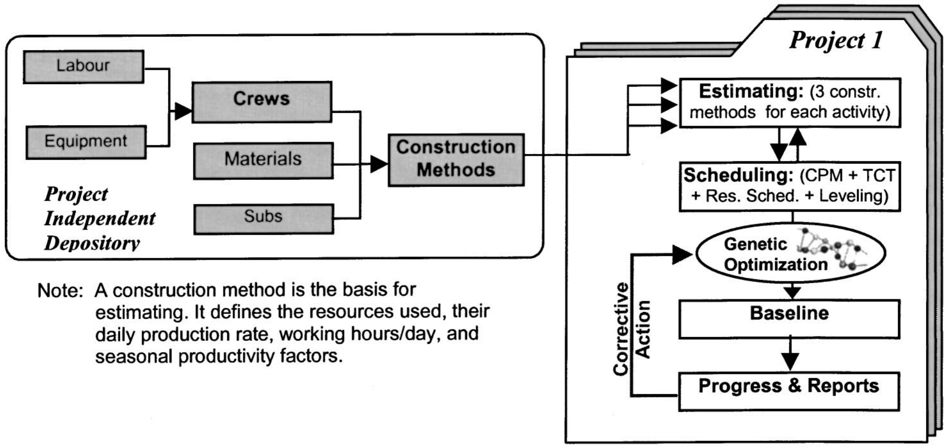

Fig. 2. Schematic diagram of proposed model

The main screen of the template is shown in Fig. 4, from which the user has access to all model components. The top section concerns the project independent depository of basic resources and construction methods. Separate sheets are used to store labor, equipment, crews, materials, and subcontractors data, including appropriate rates. Such resource data are then appropriately referenced in the "Methods" sheet that incorporates generic methods of construction with daily production rates of resources, in accordance with the RS Means cost references (RS Means Co. 2000).

In the bottom part of Fig. 4, project specific information can be input. The first was to define the activities (tasks) and their related data (Fig. 5), including: work breakdown structure levels and three methods of construction for each activity (referenced from the data depository, see note on Fig. 2) with the quantity of work involved. Based on an index that specifies which of the three methods of construction is being used, activity durations and costs are calculated. It is noted that the sheet in Fig. 5 has hidden columns to calculate a modified activity duration (D) based on the activity quantity (Q), the resource daily production (P), and the seasonal productivity factor (f) associated with the method of construction used:

$$D = Q/(P.f) \tag{1}$$

The "Estimate" sheet, as such, binds the information of all the previous sheets and links it with the "Schedule" sheet.

After specifying the activities, three critical resources ($L1$, $E3$, and $M1$ in Fig. 4) were specified in the main screen with their daily limit of 8, 1, and 35, respectively. Afterwards, using the buttons on the main screen, the specified activities were automatically transferred to a commercial project management software (Microsoft Project 2000), where the logical relationships were specified graphically. The "Schedule" sheet was then set up automatically based on the "Estimate" sheet and the task relationships imported from the scheduling software. Afterwards the user inputs the various project parameters such as deadline (28 days), indirect cost per day ($500.00), project start date (March 5, 2000), 5 working days/week, reporting period (8 days), markup (5%), retainage (10%), interest (1%), mobilization (20%), and suppliers' credit (50%). Incorporating all these variables within the formulation of CPM, TCT, cash flow, and resource computations makes the "Schedule" sheet (Fig. 6) the most dynamic and functional sheet in the template.

At this stage, the case study data was fully incorporated into

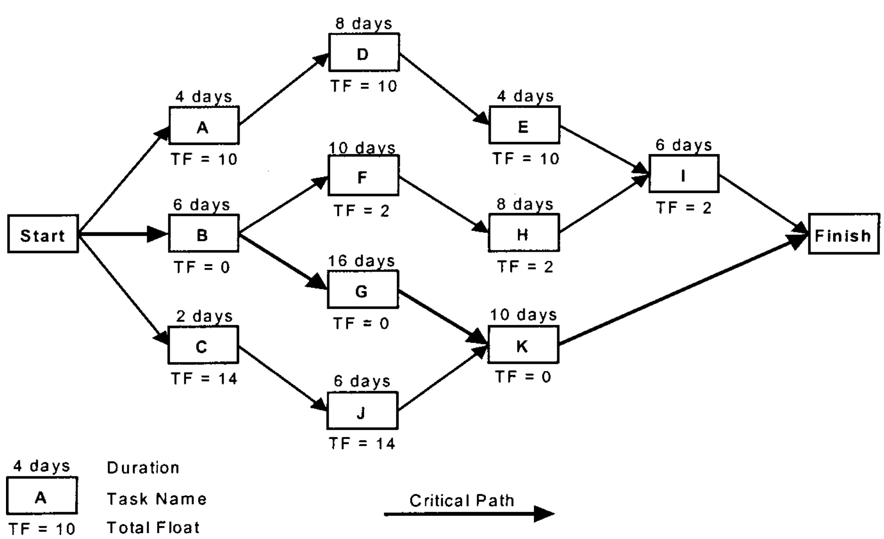

Fig. 3. Network of example project (Hegazy 2002)

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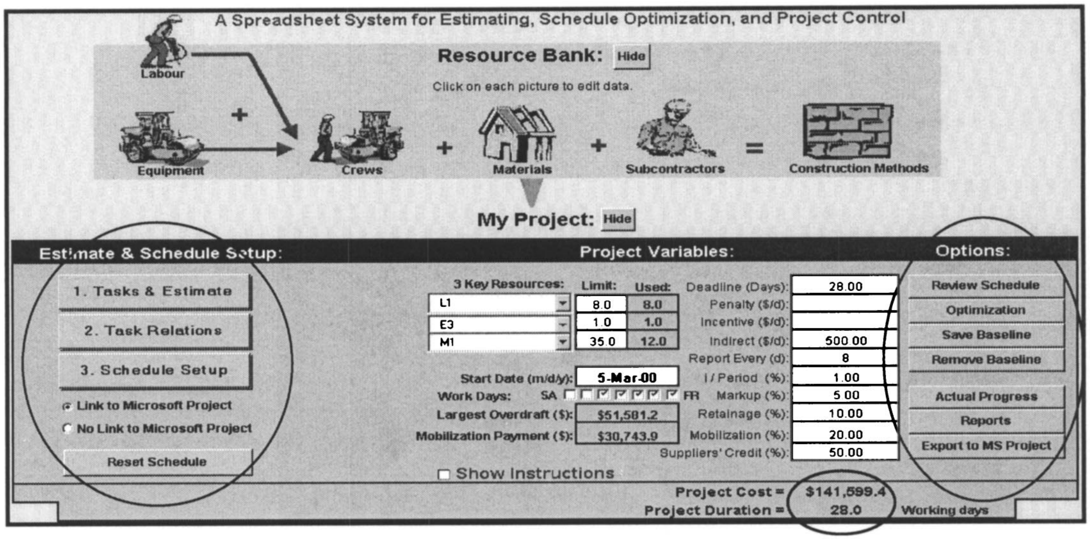
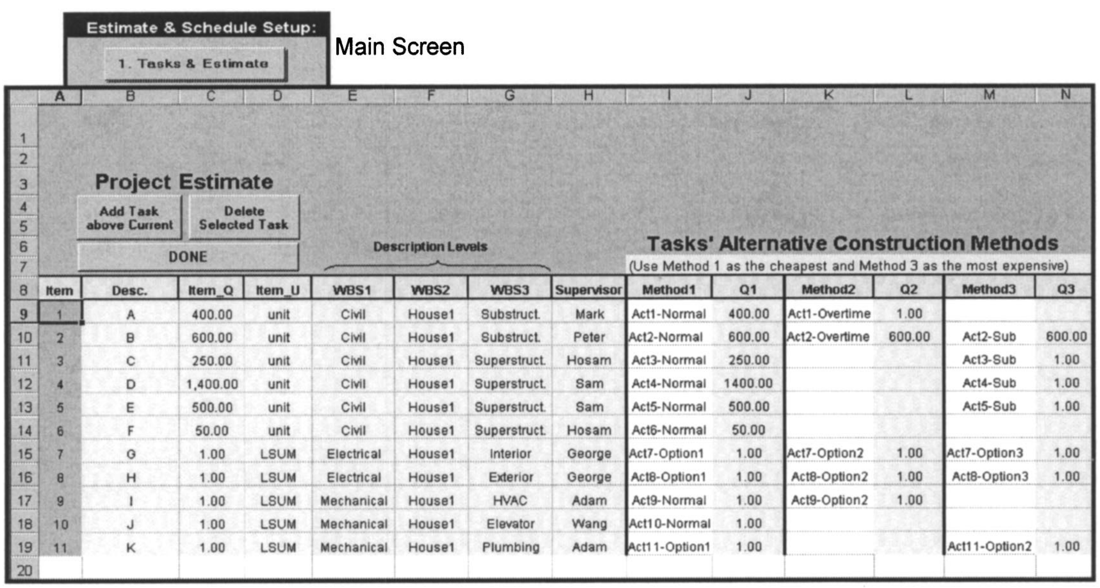


Fig. 4. Main screen of model

the model. The project had a total duration of 32 days using the durations shown in Fig. 3, associated with the cheapest method of construction for each activity. As such, the project exceeds the 28-day deadline. However, with the alternative methods of construction specified during estimating (durations and costs shown in Fig. 6), the model provides a multitude of possibilities among which an optimum plan and later corrective action can be determined. It is noted that the three marked columns in Fig. 6 show the key options that constitute the variables in developing and optimizing plans: (1) a delay column that shifts the start time of activities (needed for resource scheduling and leveling); (2) a construction method column specifying an index to one of the three methods available for each activity (needed for TCT analysis); and (3) an adjustment column that modifies the indirect costs allocated to activities (needed for bid unbalancing and cash flow improvement at the planning stage only). With the flexibility of the scheduling model, any change in the values in these columns (and certainly any resource rate, input parameter, or seasonal productivity factors, etc.) will be instantaneously reflected on project duration, cost, cash flow, and resource profiles. The model formulation also considers owner's payment scheme, mobilization payment, retainage percentage, markup percentage, overdraft interest, and suppliers' credit. Mathematical formulation and related spreadsheet modeling are discussed in Hegazy (2002).

Progress Tracking and Control

To incorporate project tracking and control features into the proposed model, a progress sheet and a reporting sheet were incorporated. The "Progress" sheet (shown later in Fig. 10) allows for input of actual daily progress, progress evaluation, earned-value



Item	Desc.	Item_Q	Item_U	WBS1	WBS2	WBS3	Supervisor	Method1	Q1	Method2	Q2	Method3	Q3
1	A	400.00	unit	Civil	House1	Substruct.	Mark	Act1-Normal	400.00	Act1-Overtime	1.00		
2	B	600.00	unit	Civil	House1	Substruct.	Peter	Act2-Normal	600.00	Act2-Overtime	600.00	Act2-Sub	600.00
3	C	250.00	unit	Civil	House1	Superstruct.	Hosam	Act3-Normal	250.00			Act3-Sub	1.00
4	D	1,400.00	unit	Civil	House1	Superstruct.	Sam	Act4-Normal	1400.00			Act4-Sub	1.00
5	E	500.00	unit	Civil	House1	Superstruct.	Sam	Act5-Normal	500.00			Act5-Sub	1.00
6	F	50.00	unit	Civil	House1	Superstruct.	Hosam	Act6-Normal	50.00				
7	G	1.00	LSUM	Electrical	House1	Interior	George	Act7-Option1	1.00	Act7-Option2	1.00	Act7-Option3	1.00
8	H	1.00	LSUM	Electrical	House1	Exterior	George	Act8-Option1	1.00	Act8-Option2	1.00	Act8-Option3	1.00
9	I	1.00	LSUM	Mechanical	House1	HVAC	Adam	Act9-Normal	1.00	Act9-Option2	1.00		
10	J	1.00	LSUM	Mechanical	House1	Elevator	Wang	Act10-Normal	1.00				
11	K	1.00	LSUM	Mechanical	House1	Plumbing	Adam	Act11-Option1	1.00			Act11-Option2	1.00

Fig. 5. Data input part of estimate sheet

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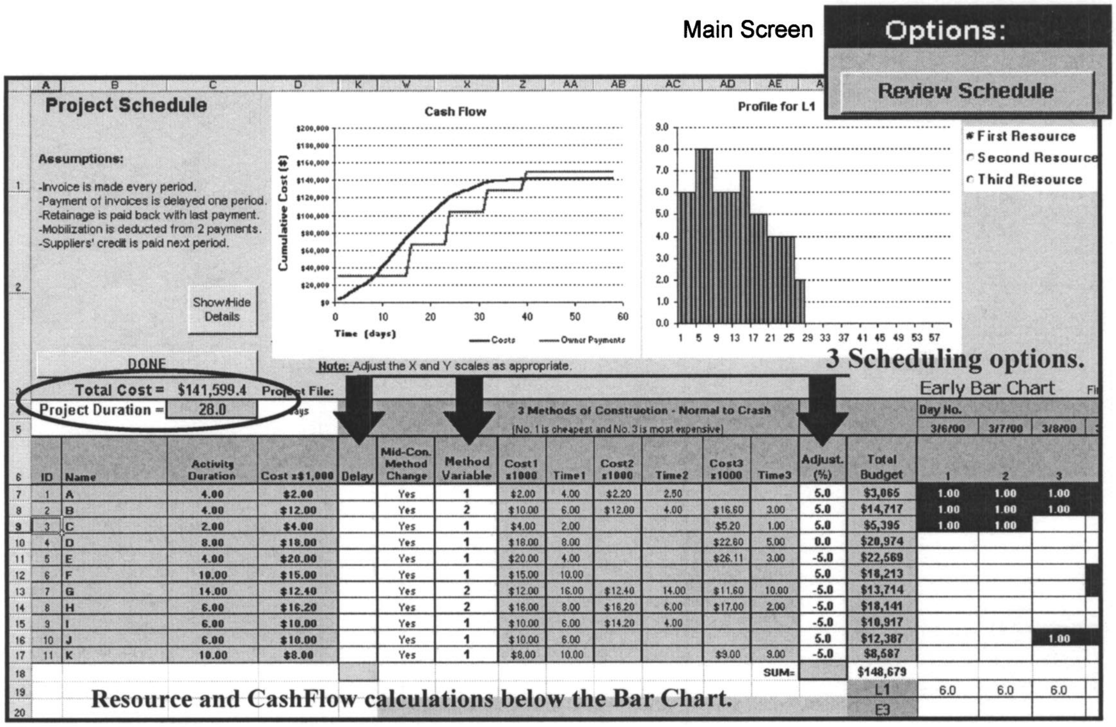

Fig. 6. Part of schedule sheet

analysis, forecasting, and progress payment evaluation. Both the schedule and progress sheets are linked to each other so that activity duration and cost, as well as the schedule bar chart (on the right side of Fig. 6) are dynamic and automatically update their values according to the user input of actual progress. To do that, activity duration and cost are formulated as direct functions of actual progress plus remaining duration. The model considers actual progress a fixed portion in the schedule and accordingly shifts the schedule of remaining work. To illustrate the formulation, an activity (i), which has started but not yet completed, is considered. As shown in Fig. 7, the activity duration is formulated as the sum of actual duration to date plus remaining duration RemDur_i as follows:

$$\text{activity duration}_i = \text{actual duration to date}_i + \mathrm{RemDur}_i \quad (2)$$

$$\text{direct cost}_i = f(\text{actual cost to date}_i\,;\mathrm{cost}_{ij}\,;\mathrm{RemDur}_i\,;\mathrm{Dur}_{ij}) \quad (3)$$

where Dur_{ij} and Cost_{ij} = duration and cost associated with method j of activity i (fixed values depending on the resources used in the method and the quantity of work). The remaining duration and direct cost, in turn, can be expressed in three ways as a function of activity percent complete (P_i) and the construction method (j) used by the activity, as follows:

1. Considering planned rate of progress (method of construction)

$$\mathrm{RemDur}_i = (1 - P_i)^* \mathrm{Dur}_{ij}$$

and

$$\text{direct cost}_i = \text{actual cost to date}_i + \mathrm{cost}_{ij}{}^*\mathrm{RemDur}_i/\mathrm{Dur}_{ij} \quad (4)$$

2. Considering actual rate of progress

$$\mathrm{RemDur}_i = \text{actual duration to date}^*(1 - P_i)/P_i$$

and (5)

$$\text{direct cost}_i = \text{actual cost to date}_i/P_i$$

3. Weighted sum of cases (1) and (2) above (6)

Eq. (4) assumes that the remaining activity work will proceed according to planned speed, ignoring if past progress was faster or slower. For example, if the activity percent complete is 30%, then the remaining 70% of the work will take 70% of the construction method duration. One benefit of this formulation is that the method of construction can be changed and accordingly, remaining duration can be reduced as a corrective action against project delay. Contrary to this, the formulation of remaining duration in Eq. (5) assumes remaining work will proceed with the same speed as the actual progress done to date. So, if the 30% complete took 4 days, then the remaining 70% will take $(4^*0.7/0.3) = 9.3$ days, regardless of the method of construction used. In this case, however, it is difficult to model the impact of corrective actions since activity duration is no longer a function of the construction method duration. Since actual progress can be somewhere inbetween these two scenarios, a weighted average, as given by Eq. (6), may provide a reasonable estimate of remaining duration. Once remaining duration is determined using Eqs. (4), (5), or (6), activity duration and direct cost are easily calculated using Eqs.

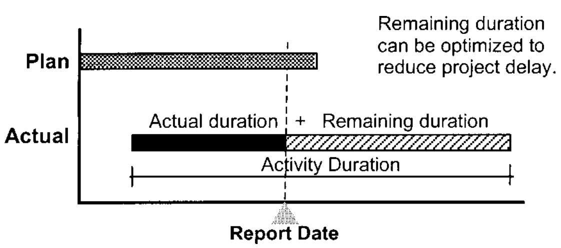

Fig. 7. Activity duration as function of remaining duration

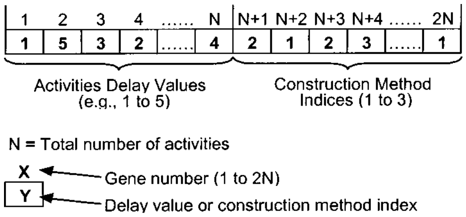

Fig. 8. Chromosome representation

(2) and (3). It is noted that at the planning stage before start of construction, activity percentage complete is zero, and the general Eqs. (2), (3), and (4), are still applicable.

One flexible option has also been incorporated into the model to consider the situation that the project manager wants to keep the method of construction unchanged for a specific task. To implement this option, column 6 in the ''Schedule'' sheet of Fig. 6, is used to specify whether or not the method of construction is permitted to change during construction. In the present case study, all values are specified as ''Yes.''

In the spreadsheet model, complete calculations for earned-value (EV) analysis are located underneath the actual bar chart in the ''Progress'' sheet (shown later in Fig. 10). It evaluates various progress indicators such as the estimate at completion, schedule performance index, and the cost performance index. These indicators provide measures of planned versus actual progress and whether the performance is improving or deteriorating. Based on these values, various charts and tables are available to view project status.

Genetic Algorithms

One unique aspect of the scheduling and control features of the proposed model is the ability to dynamically optimize the schedule before and during construction. During construction, the remaining portion of the activities is optimized based on reported progress at each reporting period. The optimization uses the genetic algorithms technique to consider for time, cost, and resource constraints. Applying the genetic algorithms technique to the model involved establishing a representation of a solution to the problem in the form of a chromosome. As shown in Fig. 8, the first half of the chromosome string consists of delay values for each activity and the second half contains construction method indices for each activity. To determine the quality of a chromosome's solution, its values are input to the model and accordingly the project duration and cost are calculated and used as measures for evaluation, along with resource amounts and resource moments, in accordance with the total-cost objective function.

The evolutionary process starts by randomly generating an initial population of parent chromosomes (pool of possible solutions). The population is then evaluated and accordingly its relative merit is calculated as the chromosome's fitness divided by the total fitness of all chromosomes. The genetic algorithms' evolutionary optimization then proceeds by simulating the reproductive process of crossover or mutation (Goldberg 1989). Crossover (marriage) is the process of combining the chromosomes of two potentially good solutions to produce an offspring. Mutation, on the other hand, produces an offspring by introducing a random variation in one of the population members. Once an offspring is generated, its fitness is then determined by copying the chromosome string of activity delay values and construction method indices into the model. If the calculated fitness (total cost) of the offspring is better (less) than that of the worst chromosome in the population, then the offspring replaces that chromosome, otherwise the offspring is discarded. Generally, the evolutionary process is conducted through a large number of offspring generations (cycles, input by user) until an optimum chromosome is arrived at. In the present application, the genetic algorithms procedure was implemented as a macro program on Excel that is automated through the user interface of Fig. 4.

Dynamic Optimization on Case Study

As mentioned earlier, schedule optimization can be carried out at both the planning and execution phases. The experiments conducted during each phase are discussed separately in the following section.

Schedule Optimization before Construction

For the case study at hand, the initial plan used the cheapest construction methods (index is 1) and arrived at a 32-day duration (4 days beyond the 28-day deadline) with the resources exceeding the limits (experiment 1 in Table 2). To improve the schedule various experiments were conducted (Table 1), as follows:

1. When project data was exported to Microsoft Project 2000 to utilize its resource leveling option, a 40-day duration was achieved with resources being within limits;
2. Using the shortest construction methods to try meeting deadline (i.e., all activities have crashed durations), a 22-day duration was achieved but cost was high ($160,515); and
3. Activating the optimization screen (Fig. 9) and proceeding with the optimization as discussed in the previous section, an optimum schedule was obtained. The resulting methods of construction and delay values are the ones shown in Fig. 6. All constraints were met including the 28-day deadline and resource limits, with minimum cost of $141,599.44 (column 5 of Table 2). The project baseline was then saved.

Table 2. Optimization Experiments before and during Construction

Experiment	All normal	Imported from MS project	All crashed	Optimized plan	Optimized plan	All crashed	Optimized progress
Phase[a]	1	1	1	1	2	2	2
Delays	0 s	Changed	0 s	0 s	0 s	0 s	Changed
Construction methods	All 1 s (cheapest)	All 1 s (cheapest)	All 3 s (shortest)	Changed	Result of planning (column 5)	All 3 s (shortest)	Changed
Cost	140,999	144,499	160,515	141,599	143,300	156,819.9	145,480.7
Duration/(days)	32	40	22	28	31	25.8	28
Resources	Violated	Within limit	Within limit	Within limit	Violated	Violated	Within limit

[a]1=planning, before construction and 2=after 8-day construction progress.

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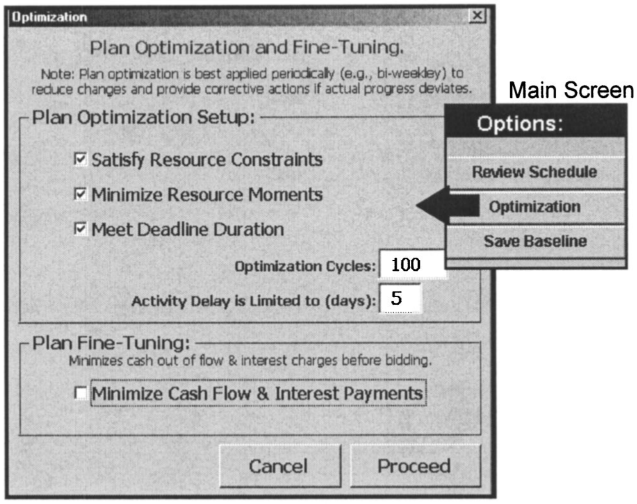

Fig. 9. Optimization options

Optimization during Construction

Dynamic schedule optimization for project control is needed after actual progress is updated in the ''Progress'' sheet (Fig. 10) and when such progress causes violation to project constraints. Based on the first 8 days of progress shown in Fig. 10, the project experienced 3 days of delay (automatically reflected in the schedule sheet). Duration became 31 days with increased cost of $143,300 (column 6 of Table 2). To improve the schedule under the 8-day progress, first effort was to use the shortest methods of construction for all activities. This resulted in 25.8-day duration but resources were violated and cost was high at $156,819.9 (column 7 of Table 2). To optimize the schedule, the optimization process was restarted. Accordingly, the remaining unfinished tasks were rescheduled with different methods of construction selected to bring the project back to within constraints. The result was a 28-day duration with resources within limits and a least cost of $145,480.7 (column 8 of Table 2). The resulting schedule (Fig. 11) shows the first 8 days being identical to actual progress, with appropriate schedule changes to the remaining work, construction methods, and delay values. This demonstrates the practicality and usefulness of the proposed model and the ability of the GA optimization process to consider actual progress and provide optimized corrective actions.

To further experiment with the optimization under the 8-day progress and with different objectives, various other experiments were conducted and results summarized in Table 3. In Table 3, experiment 1 (column 3) which focused only on meeting project deadline achieved its objective (27.5 days) in the least costly manner. This demonstrated the model's ability to effectively perform TCT analysis within possible options (some but not all of the 11 activities in the case study have optional construction methods). Each of the other experiments in Table 3, involving meeting resource limits, minimizing resource fluctuation moments, and all combined, achieved its objective in the optimum manner. The results of these experiments demonstrate that the combination of the model and GAs can generate optimized schedules during construction, consistent with project objectives.

After the schedule modifications made with the 8-day progress, it is possible to re-save the baseline and continue with progress monitoring, then repeat the process of optimizing the plan at desired intervals. It is also possible to add other methods of construction for some tasks, thus widening the space of possible solutions during optimization.

Applicability to Large Projects

In an effort to further assess the applicability and performance of the proposed model and its genetic optimization, experiments were conducted on a range of projects from small to large. The projects were constructed from the original 11-activity case study by copying the case study incrementally from 11 activities to 66 activities. Precedence relationships among the groups of activities were then specified to link the groups of activities.

The number of offspring generations for all optimization experiments was set to 5,000 cycles. The experiments were also

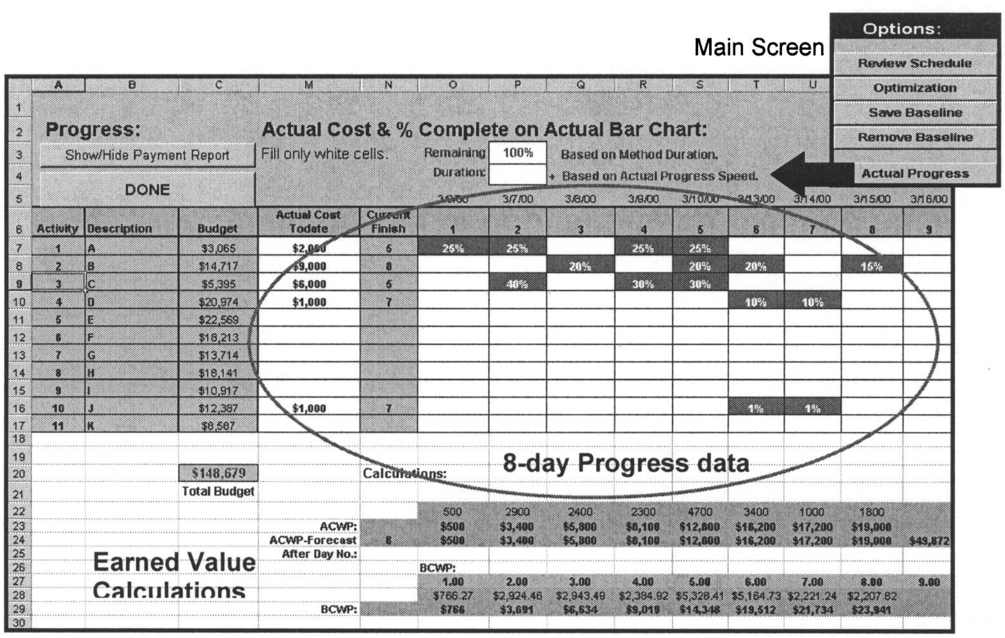

Fig. 10. Entering actual progress into ''progress'' sheet

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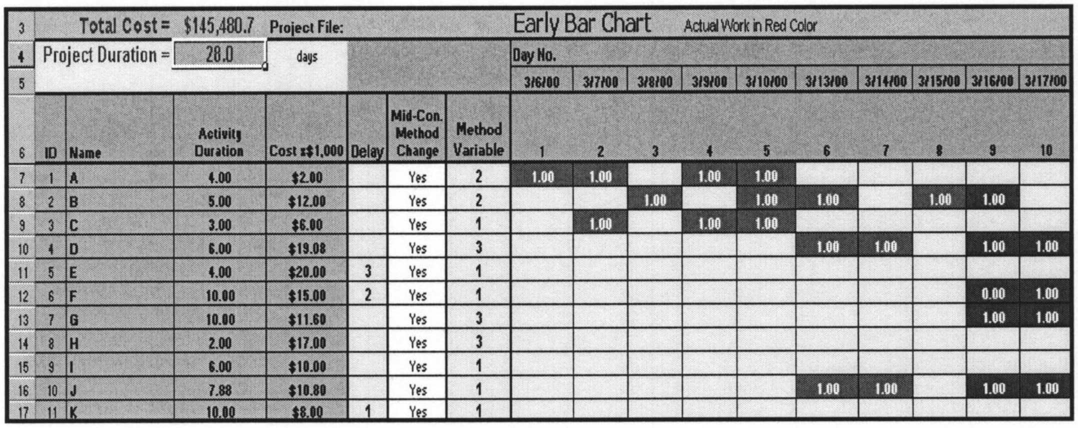

3	Total Cost = $145,480.7	Project File:						Early Bar Chart Actual Work in Red Color									
4	Project Duration = 28.0 days							Day No.									
5								3/6/00	3/7/00	3/8/00	3/9/00	3/10/00	3/13/00	3/14/00	3/15/00	3/16/00	3/17/00
6	ID	Name	Activity Duration	Cost x$1,000	Delay	Mid-Con. Method Change	Method Variable	1	2	3	4	5	6	7	8	9	10
7	1	A	4.00	$2.00		Yes	2	1.00	1.00		1.00	1.00					
8	2	B	5.00	$12.00		Yes	2			1.00		1.00	1.00		1.00	1.00	
9	3	C	3.00	$6.00		Yes	1		1.00		1.00	1.00					
10	4	D	6.00	$19.08		Yes	3						1.00	1.00		1.00	1.00
11	5	E	4.00	$20.00	3	Yes	1										
12	6	F	10.00	$15.00	2	Yes	1									0.00	1.00
13	7	G	10.00	$11.60		Yes	3									1.00	1.00
14	8	H	2.00	$17.00		Yes	3										
15	9	I	6.00	$10.00		Yes	1										
16	10	J	7.88	$10.80		Yes	1						1.00	1.00		1.00	1.00
17	11	K	10.00	$8.00	1	Yes	1										

Fig. 11. Schedule sheet with improved schedule of 28 days

performed with the progress of 8 days included. Some of the results are summarized in Table 4. In the 44-activity case with serial groups of activities, the optimization enabled the project to recover from delay, and meet resource limits with minimum cost. In the 66-activity case with parallel groups of activities, on the other hand, the optimization could for the major part resolved the stringent resource constraints (parallel activities), however, at extended project duration. One drawback associated with optimization for large projects is the extended processing time (about 6 h for the 5,000 processing cycles). However, since schedule updates and reoptimization are needed only from time to time, the proposed model can be considered applicable to small and medium-size projects and suitable for subcontractors and small–medium contractors use.

Overall Strategy for Project Control

In addition to scheduling, control, and optimization, the proposed model fully incorporates EV analysis of project progress. As mentioned earlier, the newly emerging CCPM concept has various potential benefits to improve the traditional EV approach. Perhaps the most beneficial features of the CCPM are the change in the estimating culture, the use of project buffer, and the focus on predecessors finish times. These concepts can be applied within existing project management techniques, including the proposed model, without much change to current practice. Other controversial aspects such as feeding buffers need to be reflected upon by project managers to examine their suitability to their projects.

The incorporation of the useful CCPM concepts into traditional project control, and to the proposed model in particular is suggested as follows:

1. Duration estimates for the tasks are to be determined based on 50% probability (assumes favorable working conditions with all resources readily available). This can be easily applied to the proposed model by adjusting the resource production rates (P) for the construction methods stored in the resource depository, thus leading to smaller durations, as calculated by Eq. (1);
2. Conventional CPM analysis is used to determine the project critical path since defining a resource-critical path can be difficult to determine;
3. 50% of the critical path's duration is added to the end of the critical path as a project buffer. This buffer is used for management use without being communicated to site personnel. No change in the present model, as such, is implied;
4. For monitoring and project control purposes, the conventional EV technique is to be used for cost and time variance analysis;
5. The project buffer penetration is also used as an additional monitoring tool in support of the EV technique. It is suggested that the initial baseline is kept unchanged, and accordingly no need to reoptimize the schedule, unless the project buffer is 50% consumed. This minimizes frequent changes to the schedule, particularly if optimization will determine radical changes to the construction methods that are already being used in the project; and
6. To help meet project deadlines and capitalize on early fin-

Table 3. Optimization Experiments with Different Objectives

Experiment	Initial	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Progress day	8	8	8	8	8
Optimization objective	—	Deadline	Resource limits	Deadline + moments	All combined
Project duration/Deadline	31/28	27.5/28	32/28	27/28	28/28
Total cost	$143,300	$141,050.1	$143,800	$155,294.9	$145,480.7
Resources used/Limit: *L1*	11/8	11/8	8/8	9/8	7/8
E3	1/1	1.5/1	1/1	—/1	—/1
M1	4.5/35	4.5/35	4.5/35	—/35	—/35
Total resource moment	3,783.5	3,447.3	3,829.6	1,919.3	2,519.3

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Table 4. Optimization Results for Large-Size Projects

Experiment	All normal	All crashed	Optimization	All normal	All crashed	Optimization
Number of activities	44[a]	44[a]	44[a]	66[b]	66[b]	66[b]
Optimization objective	—	Deadline	All combined	—	Deadline	All combined
Project duration/Deadline	144/112	90.5/112	106/112	72/112	49/112	146.5/112
Total cost	$571,977	$643,310	$630,631	$785,995	$921,590	$881,251.5
Resource use/Limit	8/8	30/8	8/8	22/8	21/8	9/8

[a]4 groups in series.

[b]6 groups in parallel.

ishes, a communication mechanism should be established along with an incentive scheme to encourage suppliers and subcontractors to start as soon as their predecessors are finished (see Table 4).

Summary and Concluding Remarks

In this paper, a model has been developed for carrying out dynamic project monitoring and control by means of overall optimization of project intermediate schedules. The proposed project control model was presented in the form of a spreadsheet integrated with commercial project management software and a genetic optimization procedure. The spreadsheet model, in addition to being easy to use, has a unique formulation that integrates a resource depository with various functions for estimating, scheduling, resource management, and reporting. As a general strategy for project control, some aspects of the critical chain concept can be incorporated into the proposed model without much change to traditional EV analysis. This includes the use of a project buffer, consisting of 50% of the project duration, using 50% probability estimates for task durations, and encouraging the focus on the predecessors finish rather than on scheduled start times.

Although the spreadsheet model has been demonstrated to be quite effective, there are still several aspects of the model that can be improved. The versatile bar chart of the ''Schedule'' and ''Progress'' sheets allows for multiple task-splitting representation, which the model is unable to transfer to commercial project management applications. As such, remodeling the bar charts and/or revising the data export procedure (from the model to commercial software) could possibly transfer multiple task-splitting scenarios to commercial software. Also, further revision and modification of the genetic algorithm procedure code could possibly improve the speed and the efficiency of the optimization process, and enhance its ability to arrive at quick solutions.

In general, however, the proposed model offers a familiar, flexible, and transparent environment with state-of-the-art tools suitable for subcontractors engaged in large projects, or general contractors and owners involved in small to medium-sized projects. It is hoped that practical application of the proposed model will prove to be attractive to practitioners for overall project monitoring and control in construction. For interested readers, a working copy of the application can be downloaded-from the first author's web site at www.civil.uwaterloo.ca/tarek under ''My Free Educational Software.''

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