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Development and Applications of Genetic Algorithm Enhanced Resource-Activity Critical-Path Method (GA-RACPM)

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Abstract
Development of efficient, straightforward, and computer-based methods for optimizing critical path scheduling under resource constraints is highly desired and regarded vital by construction professionals in addressing the limited availability of skilled labor and the increasing need for productivity and cost effectiveness. This paper presents follow up research of developing an enhanced version of the resource-activity critical path method (RACPM) for construction planning that minimizes the project duration using the genetic algorithm (GA). The steady-state uniform-crossover GA was adopted in optimizing the RACPM's forward pass to give the shortest project duration. A computer system called GA-RACPM was developed into an add-on tool of the MS Project to automate the GA optimization and the forward/backward pass analysis of RACPM. Applications of GA-RACPM on a benchmark project and a road improvement project in Hong Kong demonstrated the superiority of GA-RACPM over the existing resource scheduling methods, in terms of optimization performance and computing efficiency.

Keywords
Resource Scheduling, CPM, Genetic Algorithm, Optimization

1. Introduction

A 2001 industry survey by the U.S.-based Construction Financial Management Association placed "shortage of trained field help" and "shortage of trained project managers" in the first and the third spots on the list of top five challenges facing the construction industry for the 2002-2007 periods (CFMA, 2001). In the meantime, the escalating size and complexity of construction projects, the ever-tightening constraints of resources, time, and cost, and the increasingly demanding quality and environmental standards all come into play in turning the growing shortage of skilled workers and experienced managers into a global issue (Levy, 2002). In the short run, efficient, straightforward, and computer-based methods for critical path scheduling under resource constraints are regarded as being critical for construction managers to address the limited availability of skilled labor and the increasing need for productivity and cost effectiveness (Hegazy et al, 2000). Construction professionals have been using most frequently the critical path method (CPM) analysis with Microsoft Project and Primavera during both the planning and control stages in managing a project. Practitioners particularly called for enhancement of the ability of existing project management software packages to provide near-optimal schedules when resources are constrained (Liberatore et al, 2001).

Resource-constrained scheduling problems are generally classified as being *NP*-hard by computer scientists (also known as "*NP*-complete problems", "combinatorial explosion problems", or "universal search problems"). It is the recent advances in the machine learning based techniques of artificial neural networks (ANN) and GA that have opened new windows of opportunities to solve the *NP*-hard problems of resource scheduling (such as Adeli and Karim, 1997; Senouci and Adeli, 2001; Chan el al., 1996; Feng et al., 1997; Hegazy, 1999). The presence of crossover and mutating operators enables GA to find near-optimal solutions even in extremely complex discontinuous search spaces that are hard to address by techniques such as gradient descent (Duda et al., 2001). In this regard, the GA outperforms many ANN models, which are essentially adaptations of gradient descent techniques. The availability of the low-cost but high-performance GA software, plus the improved performance, robustness, and efficiency of GA itself, will bring about the day-to-day use by common practitioners of GA-based resource scheduling tools in the near future. The presented research of GA-RACPM also draws on the GA to optimize the resource-activity critical path method (RACPM) (Lu and Li, 2003) by minimizing the project duration. The computer system of GA-RACPM has been developed into an add-on tool for the MS Project, so construction professionals will, with less learning effort, be able to pick up the research deliverables and materialize real benefits in their day-to-day practice.

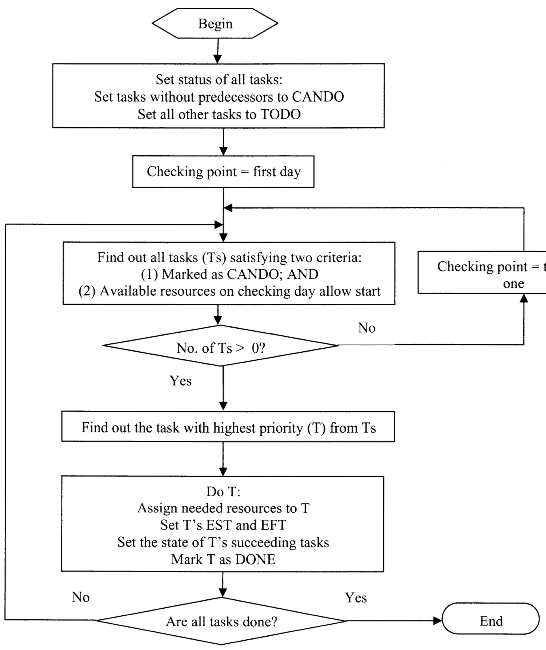

Fig.1 Flowchart of the GA-RACPM forward pass algorithm

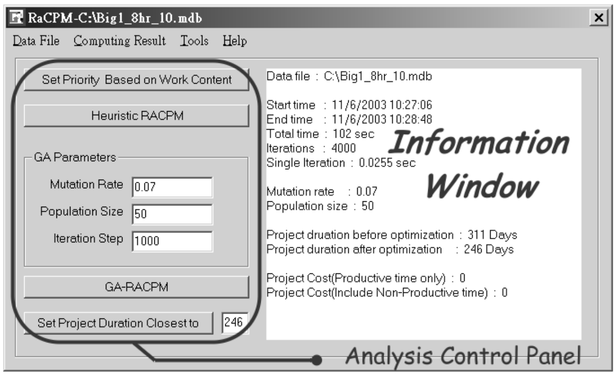

Fig. 2 Main program interface of GA-RACPM

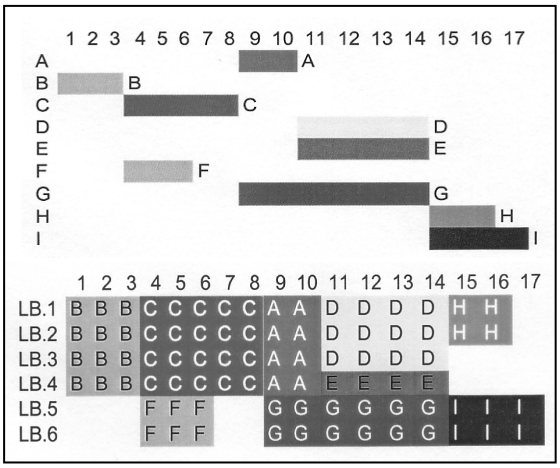

Fig. 3 Activity bar chart schedule vs. resource-activity interaction matrix

2. GA-RACPM Algorithms

The RACPM is a heuristic resource allocation approach for effectively scheduling those construction resources that are expensive, limited in quantity, and normally employed over the full project period, e.g., the skilled laborers of different trades, the major pieces of equipment used in multiple activities (such as the crane, the backhoe excavator etc.). The RACPM highlighted the dimension of resource, in addition to activity and time, in a schedule, and defined the start/finish times and the floats as resource-activity attributes based on the resource-technology combined precedence relationships: the technology-constrained ones were as in the original CPM network, while the resource-constrained ones were resulted from the forward pass resource allocation analysis (Lu and Li, 2003). The GA-RACPM's forward pass algorithm, as given in Fig. 1, is adapted from that of the original RACPM.

To encode activities' priority in a GA-based resource scheduling application, the gene structure as used in Chan el al. (1996) and Hegazy (1999) is adopted to represent the priority of each activity with random keys (also termed as biased priority, which simplifies the offspring generation procedure and hence expedite the optimization process. The fitness of a chromosome (or the corresponding RACPM schedule) is simply measured by the resultant total project duration: the shorter the project duration, the higher fitness score the chromosome achieves. The initial chromosome can be generated by assigning the work content (resource requirement multiplied by time requirement) of each activity as its initial priority key value to launch the search leading to the optimum. In the end, the priority key values, as encoded in the fittest chromosome, define the best strategy for prioritizing activities in resource allocation. The steady-state GA with uniform crossover is applied to optimize the RACPM due to its simplicity, robustness, and efficiency (Wang and Lu, 2002), as given below:

Steady-state GA.
(*L* population size, *Pco* crossover rate, *Pmut* mutation rate, *N* iterations)

```
do
   select two chromosomes with higher fitness score from the population of size L
   if Rand [0,1) < Pco then uniform crossover the pair
              else change each bit with probability Pmut
   add two new chromosomes and determine their fitness;
   rank the population and remove the two with lowest fitness score
until N iterations performed
   return highest fitness score chromosome
```

3. Development and Applications of GA-RACPM

The GA-RACPM core program was coded using MS Visual C++ 6.0 and linked through dynamic linking library (DLL) functions to supporting software systems such as Project, Excel and Access from Microsoft, which are widely used and hence can provide the end user, being a construction practitioner, with familiar interfaces for importing or exporting data. For instance, the user can easily define a CPM network and specify the limits of resources and their daily rates in the MS Project, and then use the tool provided by the GA-RACPM program to automatically read the MS Project file for the follow up GA-RACPM processing. Note that the resources, treated as groups in MS Project, are transformed into individual resource entities prior to feeding them into the GA-RACPM program. The program (shown in Fig. 2) allows three analytical functions: (1) the heuristic RACPM analysis with work-content based priority rules; (2) the GA-RACPM analysis to achieve the shortest project duration; and (3) the GA-RACPM analysis to achieve target project duration. The recommended parameters for tuning the GA are as: (1) the population size ranging from 30 to 70 is a reasonable compromise between the diversity of chromosomes and the processing time in handling projects consisting of less than two hundred activities; (2) the mutation rate of 5-10% (the corresponding crossover rate being 90 - 95%) generally avoids stagnation in optimization while leading to an expedited optimization process; and (3) 1000 to 2000 iterations are found as the appropriate choice of the interval for checking the optimization progress.

A project containing nine activities was taken from the text of Ahuja et al (1994) - an example problem used to illustrate the series method for resource loading CPM, in which a single type of labor resource is considered [Refer Ahuja et al (1994) or Lu and Li (2003) for the CPM network and activity data]. The CPM analysis without imposing resource constraints resulted in project duration of 14 days. However, given six laborers available, the project duration was prolonged to 20 days by applying (1) a series method based on the "minimum total slack" rule (Ahuja et al, 1994), (2) the heuristic RACPM under the work-content based priority rule (Lu and Li, 2003) and (3) the "automatic" resource leveling feature of MS Project 2000. With the mutation rate being 0.07, the population size being 50, and the iteration interval being 1000, running the GA-RACPM program on the project took 1 second of computer time, resulting in project duration of 17 days. The GA-RACPM generated bar chart schedule and resource-activity interaction matrix are shown in Fig. 3. The forward/backward processing results are listed in Table 1. Note that the resources working on activities B, C, G, and I have zero total floats (TF) and hence are critical; any delay on those activities leads to extension of the project duration. The resources working on Activity F (i.e. laborer no. 5 and 6 in Fig. 5) have a two-day TF, and the resource carrying out activity E (i.e. laborer no. 4) has a three-day TF, while the resources working on A, D, H have a one-day TF. The free floats can be similarly interpreted by readers.

Table 1. Input data and GA-RACPM output data for nine-activity benchmark project

Task	EST	EFT	LST	LFT	TF	FF
(1)	(4)	(5)	(6)	(7)	(8)	(9)
A	8	10	9	11	1	0
B	0	3	0	3	0	0
C	3	8	3	8	0	0
D	10	14	11	15	1	0
E	10	14	13	17	3	3
F	3	6	5	8	2	2
G	8	14	8	14	0	0
H	14	16	15	17	1	1
I	14	17	14	17	0	0

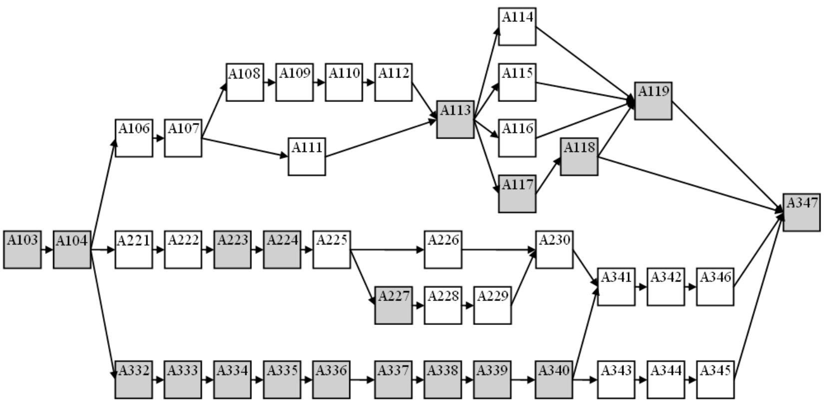

Fig. 4. CPM network for forty-two-activity road improvement project

The GA-RACPM tracks the work/idle states of individual resources over time and activity, and the resultant schedule shows explicitly the idle period for employing every laborer/equipment resource, thus allowing analysis of non-productive resources' cost and the operational efficiency. The GA-RACPM analysis also determines the resource-activity total/free floats to reflect the effect of the resources delaying the completion of activities upon extending the total project duration or affecting the early start schedules of succeeding activities. Those floats are useful for keeping the execution of the project on track, but they were not addressed in previous related developments. Finally, the GA-RACPM system features higher computing efficiency in comparison with the other related methods. For the project size of around 20 activities, the GA-based macro program by Hegazy (1999) required 60 to 140 milliseconds (ms) per iteration on a Pentium 233 MMX PC. The GA-RACPM can achieve, on average, 1 to 6 ms per iteration on a Pentium III/IV PC. Generally, it took GA-RACPM less than 10,000 iterations or within five minutes of PC time to arrive at the near-optimal schedule on real construction projects consisting of less than 100 activities.

Table 2. Resource code and practical limit imposed on resource availability in the road improvement project

Resource	Code	Available Quantity
General Labor	L01	12
Concrete Labor	L02	5
Carpenter	L03	5
Plant Operator	L04	7
Truck Driver	L05	4
Steel Worker	L06	2
Backhoe	P01	3
Truck	P02	4
Mini-bulldozer	P03	2
Steel Wheel Roller	P04	2

Lastly, a road improvement project involving ten types of limited resources and forty-two activities in Hong Kong was used to test the performance of the GA-RACPM. The project was to add two carriageway lanes and footpaths to an existing road, plus developing the drainage system and the cable network, and installing the traffic signaling system. The project CPM network is given in Fig. 4. Without resource availability constraints, the project duration was determined to be 277 days using MS Project. The practical limits imposed on the resource availability (Table 2) extended the project duration to 256 days using the standard resource leveling function provided by MS Project. The project was then imported into the GA-RACPM program, and the mutation rate, the population size, and the iteration interval were set as 0.06, of 50, and 1000, respectively. It took 51 seconds computer processing time to reduce the project duration to 246 days. From the backward pass analysis of GA-RACPM, 19 out of the 42 activities had zero total floats and hence were resource-activity critical, as shadowed in the CPM diagram (Fig. 4). Note the resource-activity critical activities do not form a complete critical path in the original CPM network. Rather, one or multiple critical paths could be readily identified in the reconstructed network diagram combining both resource-based and technology-based precedence relationships on the project (Lu and Li, 2003).

4. Conclusions

The escalating size and complexity of construction projects, the ever-tightening constraints of resources, time, and cost, and the increasingly demanding quality and environmental standards all come into play in turning the growing shortage of skilled workers and experienced managers into a global issue. In the short run, efficient, straightforward, and computer-based methods for critical path scheduling under resource constraints are regarded as being critical for construction managers to address the limited availability of skilled labor and the increasing need for productivity and cost effectiveness. This research developed a computerized method for optimal allocation and scheduling of the limited multitasking resources used in construction, by taking advantage of the latest advances in resource scheduling (i.e. RACPM) and evolutionary computing (i.e. GA). The GA-RACPM applications on benchmark and real projects demonstrated promising improvement on shortening the total project duration and the PC processing time for optimization. The GA-RACPM holds the potential to supplement the existing CPM-based project management practice and provide an optimized approach to resource scheduling, cost budgeting and progress control in construction.

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