A genetic algorithm for optimal resource-driven project scheduling

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Abstract

Resource allocation optimization is one of the most challenging problems in project management. It is a combinatorial problem with multiple objectives (project duration confinement, resource-constrained allocation, resource leveling) and its size and complexity grows exponentially as the number of activities, resource types, and execution modes increase. Existing studies bound the analysis on specific aspects of the problem or include simplifying assumptions which may not adequately represent actual (construction) projects. They typically incorporate only a few alternative activity execution modes while it is known (and also handled by popular project management software) that activities can be frequently executed in several arrangements by simply adjusting their gang size and duration. In this work, an optimization method for multi-objective resource-constrained scheduling is developed which evaluates several resource-duration alternatives within each activity. The current optimization aims at minimizing the total cost that results from (a) resource overallocation, (b) project deadline exceedance, and (c) day-by-day resource fluctuations. All three sub-objectives are represented by cost functions after assigning unit cost values to each deviation from the corresponding goal. As a result, the whole optimization parameter is a pure cost variable avoiding thus the need for subjectively setting importance weights among dissimilar parameters (as, for instance, the standard deviation of the resource histogram as a means to determine the resource levelling success). Due to the large number of activity execution alternatives, a genetic algorithm has been employed for the optimization. The algorithm has been tested with several test cases and the results were compared to those developed by the Microsoft Project. The evaluation indicates that the proposed algorithm can provide adequate and balanced solutions with regard to the three objectives and that these solutions are better than those provided by commercial project scheduling software.

Keywords: construction scheduling; genetic algorithms; optimization; resource allocation; resource leveling.

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1. Introduction

The resource-constrained scheduling problem (RCSP) has been extensively studied in the past as an important component of project scheduling analysis. The main objective is to develop optimal schedules with regard to resource allocation (subject to resource availability), resource leveling, and project duration minimization or confinement within given deadlines. In real projects, the RCSP is considerable in size and complexity. This is because (i) the analysis includes multiple and rather conflicting objectives (and corresponding set of constraints), (ii) the problem size grows exponentially with the number of project activities, resource types, and alternative activity execution modes, (iii) the number of alternative resource engagements in each activity may be large, and (iv) the problem requires finding the optimal activity gang and the appropriate activity placement in time so that the resources are optimally allocated and the resource histogram is as smooth as possible.

Existing research has produced a variety of methods and algorithms for the resource-constrained scheduling problem. They can be classified as exact methods (linear/integer or dynamic programming), heuristic algorithms, and meta-heuristic or evolutionary algorithms. Exact methods develop mathematical relationships for the objective function and the problem constraints and solve the problem with a linear or dynamic optimization technique (Davis and Heidorn [1], Bandelloni et al. [2], Adeli and Karim [3]). Although such methods have been found useful in modeling the RCSP and can provide exact solutions, their effectiveness descents rapidly as the project size and the resource alternatives increase as the solution becomes computationally intensive or infeasible.

Heuristic approaches initially develop a list of potential solutions and then apply rules for exclusion or selection of partially acceptable solutions that are likely to lead to the final (optimum or near-optimum) solution (enumeration and backtracking). A typical establishment of such methods is the branch and bound analysis which utilizes a systematic enumeration of all candidate solutions during which large subsets of fruitless candidates are discarded by using upper and lower estimated bounds of the quantity being optimized (Christofides et al. [4], Demeulemeester and Herroelen [5], Boctor [6], Mingozzi et al. [7], Brucker and Knust [8]). This type of approach poses several limitations the most important being that its efficiency depends significantly on the effectiveness of the branching and bounding algorithms used and that there is no universal bounding algorithm that works for all problems.

A number of research studies have considered the resource leveling objective. Harris [9] proposed a minimum moment method for resource leveling while Hiyassat [10] modified the original method of Harris in order to apply it to projects with multiple resources (multiple-resource leveling). Tawalare and Lalwani [11] proposed an improvement regarding the selection criterion of activities that will be moved or resource reloaded within the project duration and the resource histogram. Christodoulou et al. [12] restructured Harris’ approach as an entropy-maximization problem. This approach allows for activity stretching and provides improved resource allocation solutions compared to previous methods.

The RCSP problem attains a significant size as the number of project activities, resource types, and alternative activity execution modes increase. For this reason, the focus of most recent studies has been directed to meta-heuristic or evolutionary algorithms, primarily genetic algorithms (GA). In this class of methods, the works of Chan et al. [13], Hegazy [14], Leu et al. [15], Senouci and Eldin [16], Roca et al. [17] can be mentioned. More recently, Chen and Weng [18] have developed a two-phase genetic algorithm taking into account both time - cost trade off and resource-constrained scheduling considerations. To jointly optimize both objectives, two subsystems (time - cost trade off subsystem and resource scheduling subsystem) have been developed and operated in parallel.

Many existing studies confine their analysis to a part of the resource allocation problem (mainly resource levelling) while fewer attempt to solve the generalized problem. A general shortcoming is that they include simplifying assumptions which impede the realistic representation of actual construction projects. In order to reduce the problem size, they consider a far fewer alternative activity execution arrangements than actually existing. In particular, a couple of alternative resource modes (mainly of different type) are considered for the execution of each activity. However, they typically ignore the alternative execution options which result from the internal trade-off
between resource usage and activity duration, although this is a typical characteristic of many (construction) activities (project scheduling software highly utilize such trade-off to improve resource allocation). Further, existing methods employ only “strong” constraints with regard to resource availability or project deadline (i.e., not to be exceeded by any means). In practice, however, the exceedance of a constraint is usually feasible at an additional cost which has to be included in the optimization analysis. Finally, due to the fact that the parameters involved in multi-objective resource allocation optimization are of different physical content, it becomes necessary to subjectively set weights for the contribution of each sub-objective in order to obtain a global optimal solution.

The objective of this work is to develop an optimization model for multi-objective resource-constrained scheduling that realistically describes the resource utilization in construction activities. In particular, many activities (e.g., excavations) can be executed in several resource-duration arrangements depending on the work load, the worksite physical restrictions, etc. The proposed method aims to consider this trade-off for developing efficient resource usage schedules. Another aim of this study is to model all problem sub-objectives in a single parameter (i.e., cost) avoiding thus the need for setting importance weights among dissimilar parameters.

2. Proposed model

The optimization model that is proposed here for resource allocation involves a number of sub-objectives. All of them are considered contributing to a total cost optimization parameter which is to be minimized. The cost elements represent the direct cost for resource usage and the penalty costs for exceeding specific constraints set by the problem. In particular, the user may assign cost values for resource overallocation or project extension beyond a desired deadline. Depending on the values of the penalty costs, the corresponding constraint may be considered as “hard” (i.e., it is very costly to exceed it) or “soft” (i.e., the constrained may be exceeded without considerable cost accrual). More specifically, the cost elements of the proposed model include:

- The project direct cost represents the money spend for the resources used in the project. It is proportional to the number of resource-days that are necessary to complete the project. This cost is constant under different schedules if the number of resource-days is unchanged. Therefore, it does not affect the optimization and could be neglected; however, it is desired to know how it is compared to other, penalty-type expenditures.
- The project indirect cost is associated with the general project expenses and is applied up to the specified (desired) project completion deadline. It is distributed by day of project execution.
- The project deadline exceedance cost accounts for the (economic or other) impact or loss for the project owner as a result of not being able to use the project as planned. This cost is set per day after the project completion deadline.
- The cost of exceeding resource availability encompasses the expenditures needed to recruit additional resources than initial planned (if necessary) which may not be available or expensive to find (e.g., special purpose machinery). The cost value indicates the difficulty of finding the extra resources and may be “infinite” (e.g., extremely high) if resource exceedance is not practically feasible.
- The cost for ineffective resource usage represents the loss associated with temporal variation of resource usage within the project duration. When such variations exist, resources (human and machinery) have to move in and out of the worksite or to be idle for some time during the project execution.

Based on the above cost elements and considering the project work break-down structure and schedule (activities, dependencies, and durations) as well as the resource requirements of project activities, the proposed model involves the following sub-objectives:

- Confinement of the daily resource needs to specific availability constraints.
- Project duration minimization (or the achievement of a certain deadline).
- Utilization of a constant number of resources throughout the project.
The first two objectives are closely interconnected and, in particular, as the number of available resources decreases, the project duration increases and vice versa. The third objective is somewhat independent from the other two, however, the resource constraint usually imposes a quite leveled resource histogram (or at least without excessive fluctuations in time).

The proposed method allows resource and duration adjustment within each activity in order to develop optimal project resource usage schedules. In particular, it allows an activity to be executed with a higher or lower number of resources compared to the normal gang size. This is indicated by a range within the number of resources of each activity can vary. For instance, one can consider a ±50% acceptable deviation from the initial resource number (e.g., if, four resource units have been initially allocated to an activity, the examined range is between two and six). For each change in the resource units, the activity duration is conversely adjusted so that the total work (i.e., number of resources multiplied by the activity duration) remains constant.

Due to the substantial number of alternative activity execution options, a genetic algorithm (GA) has been employed to search for optimal solutions. An array of size equal to the number of project activities is used as the basic chromosome and its content represents a particular execution option (in terms of resource utilization) of each activity. A number of chromosomes of 10 to 50 times the number of project activities are used to form the initial population. Among them, there may be solutions that do not satisfy certain problem constraints. This however is indicated by an excessive total cost making thus unnecessary to check the validity of a specific solution. Besides, it is likely that the crossover of two constraint-breaking parents may generate constraint-satisfying children. The number of generations and other genetic operators are set dynamically depending on the problem characteristics. The GA has been implemented in MS Excel with VBA programming.

3. An application case study

A simple project with ten activities is considered to illustrate the algorithm application. The project activities, the precedence relationships, the activity durations, and the normal resource requirements for each activity are shown in Table 1. A single resource type for all activities is considered for simplicity. The network diagram of the example project is presented in Figure 1. Figure 2 illustrates the Gantt chart and the resource histogram of the initial scheduling solution (presented as an Ms-Project output). The normal project duration is 18 days and the maximum resource requirement is 14 units.

The evaluation has considered a number of scenarios representing different sub-objective prioritizations. This is done by adjusting the relative unit costs of the optimization parameters (resource availability exceedance, project deadline exceedance, number of resources in and out of production within the project length). In particular, each individual parameter is initially considered with high cost value compared to the other two. Following, other test cases are considered with comparable cost values among the three sub-objectives to examine the degree in which the solution copes with the given priorities and constraints.

The results of some indicative test cases are presented in Table 2 and include in each case the project duration, the maximum resource usage, the standard deviation of the resource usage, and the cumulative resource units in and out of the project throughout its duration (the initial resource loading and final decommissioning are not included as being unavoidable). Case 1 represents the initial project schedule and resource histogram. Case 2 provides the result of the optimization assuming a high cost value for project deadline exceedance and considerably lower ones for resource overallocation and resource fluctuations. Cases 3, 4 and 5 correspond to cost values of 1000 units per overallocated resource unit (above the limit of 8 units per day), 300 cost units per day of project delay beyond the normal duration (18 days) and 100 cost units for each resource unit entering in or exiting from the production. Finally, case 6 represents the best manual solution for this problem.
Table 1. Project data for the application example.

| Activity | Predecessor | Duration | Resource # | Activity | Predecessor | Duration | Resource # |
|----------|-------------|----------|------------|----------|-------------|----------|------------|
| A        | -           | 3        | 4          | F        | C           | 5        | 6          |
| B        | A           | 2        | 3          | G        | D           | 4        | 4          |
| C        | A           | 5        | 2          | H        | G           | 5        | 4          |
| D        | B           | 2        | 5          | I        | E           | 4        | 3          |
| E        | C           | 2        | 4          | J        | F           | 5        | 4          |

Figure 1. Network diagram of the example project

Figure 2. Gantt chart and resource graph of the original project schedule

It is observed that the proposed model can handle different scenarios and provide reasonable results in each case. The resource constraint (where present) is always satisfied (due to the high cost of exceeding it) and quite leveled resource histograms are accomplished (as indicated by the low standard deviation and the cumulative resource fluctuation parameter compared to case 1). The comparison of cases 3 and 4 indicates that the capability of adjusting the resource assignment within each activity improves both the project duration and the resource histogram shape.
The model responds well to existing constraints and available scheduling options (Figure 3) in comparison to Ms-Project which seems to develop a limited number of scheduling options, the best of which is shown in Figure 4. Both methods, however, lack behind the results obtained manually for this (small) project (Table 2). Nevertheless, a manual solution may not be feasible in large project or in projects with multiple resource types.

Table 2. Results for example project.

| Case no | Case description                                      | Resource constraint | Project duration | Max resource usage | Resource standard deviation | Cumulative resource fluctuations |
|---------|-------------------------------------------------------|---------------------|------------------|--------------------|-----------------------------|---------------------------------|
| 1       | Initial early time schedule                          | -                   | 18               | 14                 | 3.91                        | 22                              |
| 2       | Resource allocation within available slacks           | -                   | 18               | 11                 | 2.74                        | 12                              |
| 3       | Resource allocation under resource constraint – no activity resource adjustment permitted | R ≤ 8               | 24               | 8                  | 1.77                        | 16                              |
| 4       | Resource allocation under resource constraint – activity resource adjustment permitted – GA solution | R ≤ 8               | 22               | 8                  | 1.02                        | 2                               |
| 5       | Resource allocation under resource constraint – activity resource adjustment permitted – Ms-Project solution | R ≤ 8               | 24               | 8                  | 1.44                        | 14                              |
| 6       | Resource allocation under resource constraint – activity resource adjustment permitted – manual solution | R ≤ 8               | 19               | 8                  | 0.69                        | 4                               |

On the basis of the results presented above and from further elaboration with other case studies, the following remarks can be written:

- The prudent use of resources in (construction) projects is of major importance for the timely and economical completion of them. Unnecessary money leakage can result from many origins and all these must be appropriately considered in project and resource planning.
- The consideration of several different modes for executing project activities may impede the effort to develop continuous and constant resource use. Instead, the employment of fewer mode types in conjunction with internal reorganization of activity execution (resource loading and duration adjustment) can lead to more productive resource utilization and cost reduction.
- By considering actual cost values for each undesirable deviation, the parameter that is optimized attains a real, tangible measure of effectiveness which can be easily evaluated. The unit costs assigned to individual parameters represent the relative importance and priority of them in each particular project.
- Simple statistical (or similar) measures to model a clearly cost-related parameter may not be as effective in a project management optimization model With reference to Figure 3, a hypothetical resource allocation diagram with continuous resource fluctuations between 6 and 8 would have the same standard deviation as the histogram in Figure 3. However, the actual cost would be obviously quite different in the two cases.
- The resource-constraint scheduling problem is a large and complex one as activities should be optimally shaped in terms of resource units and duration and placed at the right time frame within the project satisfying also the precedence relationships as well as any resource availability and completion deadline constraints. As a result, soft computing (evolutionary) algorithms seem to be more appropriate for solving the problem than exact optimization methods.
- A decreasing efficiency is observed in all solution methods as the project size (number of activities) and/or resource types increase and this is anticipated since the solution space increase significantly. Nevertheless, the proposed model seems to perform better than the corresponding one in Ms-Project. If one then considers the cost of machinery idling and time wasted due to improper resource and work scheduling in actual construction projects, even a small improvement in resource usage and time planning can bring a notable return.
4. Conclusions

The resource-constrained scheduling problem is one of the most challenging ones in the area of project management. This is a combinatorial optimization problem with multiple and conflicting objectives and constraints, i.e., confine the daily resource usage within resource availability, finish the project as soon as possible, and make the daily resource histogram as smooth as possible. The problem gains significant size as the number of project activities, resource types, and alternative activity execution modes increase. For this reason, existing studies bound the analysis on specific aspects of the problem or include simplifying assumptions which may not adequately represent actual (construction) projects.
In this work, an optimization model is developed for multi-objective resource-constrained scheduling which evaluates several resource-duration alternatives within each activity. The optimization aims at minimizing the total cost that is associated with (a) resource overallocation, (b) project deadline exceedance, and (c) day-by-day resource fluctuations. All three sub-objectives are represented by cost functions and the whole optimization parameter is a pure cost variable avoiding thus the need for subjectively setting importance weights among dissimilar parameters. Due to the large number of activity execution alternatives, a genetic algorithm has been employed for the optimization. The algorithm has been extensively tested with several test cases and the results have been compared to those developed by the Microsoft Project. The evaluation indicated that the proposed algorithm can provide adequate and balanced solutions with regard to the three objectives and that these solutions are better than those provided by commercial project scheduling software.

References

[1] E. Davis, G. Heidorn. An Algorithm for Optimal Project Scheduling Under Multiple Resource Constraints. Management Science 17 (1971) 803-816.
[2] M. Bandelloni, M. Tucci, R. Rinaldi. Optimal Resource Levelling Using Non-serial Dynamic Programming. European Journal of Operational Research 78 (1994) 162-177.
[3] H. Adeli, A. Karim. Scheduling/Cost Optimization and Neural Dynamics Model for Construction. Journal of Construction Engineering and Management 123 (1997) 450-458.
[4] N. Christofides, R. Alvarez-Valdes, J. Tamarit. Project Scheduling with Resource Constraints: A Branch and Bound Approach. Computers and Industrial Engineering 12 (1987) 227-242.
[5] E. Demeulemeester, W. Herroelen. A Branch-and-Bound Procedure for the Multiple Resource-Constrained Project Scheduling Problem. Management Science, INFORMS 38 (1992) 1803-1818.
[6] F. Boctor. Some Efficient Multi-heuristic Procedures for Resource-constrained Project Scheduling. European Journal of Operational Research 49 (1990) 3-13.
[7] A. Mingozzi, V. Maniezzo, S. Ricciardielli, L. Bianco. An Exact Algorithm for the Multiple Resource-constrained Project Scheduling Problem Based on a new Mathematical Formulation. Management Science 44 (1998) 714-729.
[8] P. Brucker, S. Knust. Lower Bounds for Resource-constrained Project Scheduling Problems. European Journal of Operational Research 149 (2003) 302-313.
[9] R. Harris. Packing Method for Resource Leveling (PACK). Journal of Construction Engineering and Management 116 (1990) 331 – 350.
[10] M. Hiyassat. Applying Modified Minimum Moment Method to Multiple Resource Leveling. Construction Engineering and Management 127, 3 (2001) 192-198.
[11] A. Tawalare, R. Lalwani. Resource Leveling in Construction Projects using Re-Modified Minimum Moment Approach. World Academy of Science, Engineering and Technology 62 (2012), 33-35.
[12] S. Christodoulou, G. Ellinas, A. Michaelidou-Kamenou. Minimum Moment Method for Resource Leveling Using Entropy Maximization. Journal of Construction Engineering and Management 136, 5 (2010) 518-527.
[13] T. Chan, H. Chua, G. Kannan. Construction Resource Scheduling with Genetic Algorithms. Journal of Construction Engineering and Management 122, 2 (1996) 125 – 132.
[14] T. Hegazy. Optimization of Resource Allocation and Levelling Using Genetic Algorithms. Journal of Construction Engineering and Management 125, 3 (1999) 167-175.
[15] S. Leu, C. Yang, J. Huang. Resource Leveling in Construction by Genetic Algorithm-Based Optimization and its Decision Support System Application. Automation in Construction 10 (2000) 27-41.
[16] A. Senouci, N. Eldin. Use of Genetic Algorithms in Resource Scheduling of Construction Projects. Journal of Construction Engineering and Management 130, 6 (2004), 869-877.
[17] J. Roca, E. Pagnaghi, G. Libert. Solving an Extended Resource Leveling Problem with Multi-objective Evolutionary Algorithms. International Journal of Information and Mathematical Sciences 4, 4 (2008) 289-300.
[18] P. Chen, H. Weng. A Two – Phase GA Model for Resource - Constrained Project Scheduling. Automation in Construction 19 (2009) 485-498.