Creative Construction Conference 2019, CCC 2019, 29 June - 2 July 2019, Budapest, Hungary

Resource-constrained scheduling in repetitive projects

Athanasios P. Chassiakos, Marialena Koptsopoulou, Stavroula P. Deligianni

Department of Civil Engineering, University of Patras, Patras, 26500, Greece

Abstract

The optimal allocation of resources is a critical factor for the successful implementation of construction projects since it ensures stability in the work execution. Resource allocation is a complex optimization analysis, especially when it comes to linear or repetitive projects. In such projects, the Line of Balance scheduling method is preferred to the CPM-based scheduling. This study aims at developing a multi-objective model for optimizing resource allocation in such type of projects under different objective criteria and problem constraints. The practical implications of each criterion in terms of project cost are considered to provide some guidance on what criterion may be more suitable under particular circumstances. The optimization is obtained through a genetic algorithm formulation implemented in a spreadsheet form and with the use of a commercial optimization software. Indicative evaluation results are presented on the basis of a case study and show that criteria involving as decision parameters the cumulative exceedance of resources above a given resource availability threshold or the total number of resource movements in and out of the project may be the most appropriate to simulate actual costs and provide effective resource allocation solutions.

© 2019 The Authors. Published by Budapest University of Technology and Economics & Diamond Congress Ltd.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: resources allocation; resource leveling; optimization; genetic algorithms; line of balance method; repetitive projects.

1. Introduction

The problems of resource-constrained scheduling and optimal resource allocation are of crucial importance in project planning and implementation as well as in cost control. The challenge in optimizing resource usage and project duration emerges from the fact these parameters inversely affect each other. In particular, if a reduced project duration is sought, the resource requirements are increased and resource leveling becomes more challenging adversely affecting the project cost and vice versa. Therefore, certain combinations of the input parameter values which lead to a suitable balance between the two objectives are sought. Optimal resource allocation refers to both restricting the resource requirement within the availability limit and smoothing resource usage throughout project execution to enhance stability and quality of the construction process.

In case of linear or repetitive projects (e.g., high-rise buildings, complexes of identical residences, tunnels or pipelines), the difficulty of optimization is remarkably increased. A basic technique for scheduling linear projects is the Line of Balance (LOB) method which can further assist in performing the time-resource optimization. The LOB technique, originally designed by the Goodyear Company in the early 1940s and further developed by the U.S. Navy in the 1950s, has been used as a planning and scheduling technique in the construction sector since the early 1970s. Carr and Meyer (1974) presented the LOB technique in its present form [1]. In the following years, attempts were made that resulted in revised and extended scheduling models and tools based on this method [2-7].

Resource allocation and management in construction has been extensively studied in the past and several works have been reported in the literature. The majority of them have been developed based on the CPM scheduling technique (indicative works can be found in [8-13]). In contrast, there are fewer efforts structured on the LOB method and, among them, are those found in [14, 15]. Existing works present two types of limitations. First, they mainly focus on resource leveling and not as much to the general multi-objective, multi-constraint resource management problem. Next, the decision parameters are somewhat theoretical and not entirely representing more practical effects. For instance, the main parameter for resource leveling is traditionally some type of statistical moment of the obtained resource histogram. Although such a parameter is mathematically sound for a theoretical analysis, there is no direct explanation of the effect that a non-uniform resource diagram has on the project cost. To account for such discrepancies between theoretical and practical considerations of the decision parameter(s) and to obtain a more complete view of the effectiveness of different decision criteria, the present study analyzes and evaluates alternative optimization structures and criteria based on practical implications of those structures and criteria.

2. Proposed Model

Resource allocation problems are associated with two main parameters, the number of resources used day by day and the project duration, and aim at finding a balance between them. Exceeding the project time limit typically incurs additional cost in the form of a penalty or as a result of the project not being operational for some planned period. Additional cost may also take place if the project asks for more resources than available at any time period during the project execution. Further, another cost component is present if the resource diagram is not levelled with this cost to represent the expenditures for bringing in and letting out (or keeping idle) resources during the project execution. In fact, resource levelling usually softens the resource overallocation problem (except if very strict resource availability exists) since there are no large resource peaks that extensively exceed the constraint.

In this work, a number of modelling techniques to improve the resource graph of a repetitive type of project, based on time and resource availability constraints, are presented and compared. The main parameters and the mathematical relationships that govern the scheduling of repetitive projects are the following. If C is the number of crews used in an activity and t is the activity duration in one unit, then the production rate P is calculated as:

$$P = \frac{C}{t} \quad (1)$$

Further, the start time of the activity at the n -th unit, t_n , is given by the equation:

$$t_n = t_1 + \frac{1}{P} * (Q_n - 1) \quad (2)$$

where t_1 is the start time of the first unit and Q_n is the number of units that have already been produced; the finish activity time in the n -th unit is calculated by adding the activity duration t to the start time of the same unit.

In order to smooth out the project resource diagram, the optimization model considers two types of (independent) variables, the number of crews in each activity and the time lags between activities. Controlling such variables allows to adjust to any desirable resource level and to avoid activity accumulation at certain time frames. The problem, however, has two conflicting objectives, resource confinement/levelling and project duration restriction. The second parameter is taken into account in this study as a model constraint. Other constraints include the number of available crews and the maximum time lag permitted between consecutive activities in order to keep the number of feasible solutions manageable.

Individual objectives of the optimization structure are the following:

- Minimization of the maximum resource peak (maxR) for a specific project completion deadline. This process can be thought as a “piston” that presses the resource peaks down towards a finally levelled diagram.
- Minimization of the cumulative resource excess above the resource availability level (ExcessBaseR). The optimization parameter in this case is the sum of the resource surplus over the resource availability threshold in time. This criterion may be associated with the fact that extra resource may be engaged at a higher than the usual resource unit cost (e.g., overtime work). To avoid isolated extreme resource peaks, the daily resource exceedance values may be considered with some exponential form.

- Minimization of the standard deviation of the daily resource values (StDevR). This is a common criterion used for resource levelling. In fact, from the mathematical point of view, such a criterion macroscopically develops a quite levelled resource diagram, in practical terms however, it cannot avoid the continuous fluctuations of the diagram values from day to day, a situation that is not desirable in projects.
- Minimization of the resource movements in and out of the project in time (SumΔR or CountΔR). This criterion aims to minimize the resource movements avoiding or reducing the corresponding cost (both economic and “social” – the morale of workers from an unsteady working status). Depending on how the cost develops, either the sum of the resource movements or the number of times that a movement (of one or more resources) is needed (or both) can be considered as the optimization parameter.

The above parameters have been included in a multi-objective objective function of the following form:

$$\min F = w_1 * \max_R + w_2 * Excess_{BASER} + w_3 * StDev_R + w_4 * Sum\Delta R + w_5 * Count\Delta R + w_6 * D \quad (3)$$

where $w_1, \dots, w_6$ are weights for the individual parameters associated with the cost resulting from any particular “deficiency” of the resource allocation diagram. The project duration D has also been included in (6) as a decision parameter and can be considered, in combination with any other resource-related parameter, as a secondary objective (i.e., with relatively low weight value) to obtain the lowest possible duration after optimizing the primary objective.

Based on the above analysis and depending on the parameters of a specific scheduling solution, the number of resources per activity can be calculated at every time period leading to the cumulative (for all activities) project resource diagram. This process has been implemented in an Ms-Excel spreadsheet and the resource graph is automatically produced with all quantitative characteristics that describe the effectiveness of the solution in accomplishing the optimization objectives. Figure 1 shows the graphical results obtained automatically by the software for a specific solution; (a) the LOB diagram of the solution; (b) the individual resource allocation for each project activity (corresponding to the LOB diagram); and (c) the cumulative project resource allocation diagram. The optimization is performed through genetic algorithms (GAs) via a commercial optimization software (Palisade Evolver 7.5) which works as an Excel add-in.

3. Case study

A case study example illustrates the project scheduling and resource allocation under different optimization criteria for a construction project referring to a complex of 20 similar residences (150m² each). The project input data are presented in Table 1. For each activity, the optimal crew size (based on a balanced time-cost configuration) and the required hours for the completion of one unit (residence) are inserted. The duration of a complete unit is calculated by considering an 8-hour daily working time.

Figures 1-4 present the optimization results for each of the optimization criterion described previously (a 350-day constraint for the project completion is set). In particular, Figure 1 provides a representative output for the $\min\{\max R\}$ criterion. The result indicates a somewhat levelled resource allocation diagram with a maximum resource value of 35. Figure 2 depicts the resource allocation diagram resulting from the cumulative daily resource exceedance above a certain limit (a threshold of 30 available resource units daily has been considered in this application). The resulting resource diagram is quite smooth with very few peaks up to the level of 35. Figure 3 indicates an optimal resource diagram following the standard deviation criterion. The general view indicates a rather smooth diagram, however, there are several and frequent ups and downs that are not desirable from a practical point of view. Figure 4 shows the resource diagram resulting from minimizing the cumulative resource movements in and out of the project throughout its execution. Rather unexpectedly, the diagram is not levelled; instead, it presents a progressive development which, however, is smoother than any other previous diagram. In case, therefore, that the main cost component is associated with the resource movements in and out of the project and there is no constraint on resource availability, such a solution may be of the lowest cost.

Table 1. Case study input data

Activity code	Activity	Optimal crew size	Hours required for one unit	Activity code	Activity	Optimal crew size	Hours required for one unit
A	Excavation	5	120	H	Water Supply	3	100
B	Foundation	5	240	I	Electrical Installations	2	160
C	Concrete	5	520	J	Heating system & A/C	2	140
D	Masonry	6	300	K	Paintings	4	480
E	Roughcast	4	360	L	Insulation works	4	320
F	Doors & Windows	3	96	M	Landscaping	5	600
G	Floors	4	300

Fig. 1 Resource allocation diagram for the minimization of max R
(a) LOB diagram; (b) individual activity resource diagram; (c) whole project resource diagram

Fig. 2 Resource allocation diagram for the minimization of excess of base R

Fig. 3 Resource allocation diagram for the minimization of the standard deviation

Fig. 4 Resource allocation diagram for the minimization of the cumulative resource movements

Although differences are not extreme, the experimentation with the current and other case studies provide some indications that the cumulative excess of the resource limit criterion may be the most appropriate for resource levelling in practical applications while the cumulative resource movement criterion may be primarily used if the corresponding cost is prevailing. Combination of these two (or any other) criteria, based on weight balancing, can provide intermediate solutions forming Pareto curves between optimization parameters.

4. Conclusions

The resource allocation problem is a difficult combinatorial problem which aims to develop an optimal balance between the resource usage and the time required for project completion. Scheduling projects of linear or repetitive

structure based on the CPM technique is challenging and, for that reason, the employment of the Line of Balance method has prevailed in such cases. In this work, a multi-objective model for optimizing resource allocation under different objective criteria and problem constraints is presented. The practical implications of each criterion in terms of project cost are considered to provide some guidance on what criterion may be more suitable under particular circumstances. Five such criteria are comparatively evaluated, namely the minmax R_i criterion (R_i indicates the daily resource requirements of a particular scheduling solution throughout the project execution), the cumulative excess of the resources required daily in comparison to the resource availability during the project execution, the standard deviation of the resource histogram, and the total number of resource movements in and out of the project all over its duration in two distinct forms, the sum of resource moved or the number of times that some resource movement takes place.

The model has been implemented in a spreadsheet environment with all inputs, calculations, and outputs to be handled by the software while the optimization is obtained through a genetic algorithm and employing a commercial optimization software that comes as an add-in to the spreadsheet software. Results from a case study presented in the present work and further experimentation indicate that, although there are no extreme deviations in the results, objective criteria involving as decision parameters the cumulative exceedance of resources above a given resource availability threshold or the total number of resource movements in and out of the project may be the most appropriate to simulate actual costs and provide effective resource allocation solutions.

References

- [1] R.I. Carr and W.L. Meyer, Planning construction of repetitive building units, *Journal of the Construction Division* 100(3) (1974) 403-412.
- [2] T. Hegazy, O. Moselhi, and P. Fazio, BAL: An algorithm for scheduling and control of linear projects, *AACE Transactions*, Morgantown, West Virginia (1993) 8.1–8.14.
- [3] C. Wang and Y. Huang, Controlling activity interval times in LOB scheduling, *Construction Management and Economics* 16(1) (1998) 5-16.
- [4] R.B. Harris and P.G. Ioannou, Scheduling projects with repeating activities, *Journal of Construction Engineering Management*, 124(4) (1998) 269–278.
- [5] D. Arditi, O.B. Tokdemir, and K. Suh, Scheduling system for repetitive unit construction using line-of-balance technology. *Engineering, Construction and Architectural Management*, 8(2) (2001) 90-103.
- [6] O.B. Tokdemir, D. Arditi, and C. Balcik, ALISS: Advanced Linear Scheduling System, *Construction Management and Economics*, 24(12) (2006) 1253-1268.
- [7] Firat, D. Arditi, J.P. Hämäläinen, and J. Kiiras, Extended model-based master scheduling for building projects using advanced line of balance, *Proceeding of 26th CIB W78 Conference-Managing IT in Construction*, Istanbul Turkey, 2009.
- [8] T. Hegazy, Optimization of resource allocation and leveling using genetic algorithms, *Journal of Construction Engineering and Management*, 125(3) (1999) 167-175.
- [9] 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.
- [10] A. Senouci, N. Eldin. Use o Genetic Algorithms in Resource Scheduling of Construction Projects. *Journal of Construction Engineering and Management* 130, 6 (2004), 869-877.
- [11] P.H. Chen and H. Weng, A two-phase GA model for resource-constrained project scheduling, *Automation in Construction*, 18(4) (2009) 485–98.
- [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] S. Kaiafa and A.P. Chassiakos, A genetic algorithm for optimal resource-driven project scheduling, *Procedia Engineering* 123 (2015) 260-267.
- [14] A. Damci, D. Arditi, and G. Polat, Multiresource Leveling in Line-of-Balance Scheduling, *Journal of Construction Engineering and Management*, 139(9) (2013) 1108-1116.
- [15] A.P. Chassiakos and S.P. Deligianni, Resource allocation in Line-of-Balance scheduling *Proceedings of the Eighth International Conference on Construction in the 21st Century*, Thessaloniki, Greece, 2015.