Resource Allocation in Line-of-Balance Scheduling

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Abstract
The Line of Balance (LOB) is a scheduling technique for managing work flow in projects with repetitive characteristics. The objective of this study is to develop optimal resource allocation solutions in such projects using the LOB technique. The resource allocation process leads to a combinatorial optimization problem with multiple and partially contradictory objectives, i.e, confinement of the daily resource usage within resource availability, project completion within a given deadline (or as soon as possible), and making the resource diagram as smooth as possible. The proposed model aims to concurrently optimize all the above subgoals depending on their relative importance (multi-objective resource-constrained scheduling). Due to the size of the solution space, a genetic algorithm has been employed to perform the optimization. The model has been applied to a pipeline project and tested under several constraint and subgoal scenarios. The evaluation has indicated the ability of the model to provide reasonable and targeted solutions in response to given priorities and constraints. In conclusion, the LOB technique can be effectively used for optimal resource allocation in repetitive projects.

Keywords
Line-of-balance, resource allocation, optimization, genetic algorithms, repetitive projects

1. Introduction

Linear scheduling methods are planning and scheduling techniques mostly used in cases where operations are of repetitive nature. Highways, high-rise buildings, tunnels and pipelines are good examples that exhibit repetitive characteristics. In these projects, similar activities are repeated sequentially in different units of the project which may demand special attention and implementation plan. Although network based methods, such as the Critical Path Method (CPM), are proven to be powerful scheduling and progress control tools, they are not very suitable for the aforementioned projects. An appropriate method for repetitive projects is the Line of Balance (LOB) method which is a variation of linear scheduling methods that allows the balancing of operations such that each activity is continuously performed. The main advantage of the LOB methodology is that it provides production rate and duration information in the form of an easily interpreted graphical form. The LOB plot can show at a glance any deficiency with regard to the progress of an activity and can detect potential future bottlenecks. Subsequently, it allows a better grasp of a project composed of repetitive activities than any other scheduling technique because it allows adjusting the production rates of activities. It further allows a smooth and efficient flow of resources, and requires less time and effort to produce than network schedules (Arditi and Albulak 1986).

The LOB technique was originally designed by the Goodyear Company in the early 1940s and was developed by the US Navy in early 1950s to manage both repetitive and non-repetitive projects (Neale 1989). It was later enhanced by the National Building Agency in UK for repetitive housing projects.

Lumsden (1968) modified the basic LOB technique and applied it to house construction scheduling. He explained in detail the principles, representation, and analysis of the method. Khisty (1970) applied the LOB technique to construction in the classical sense of manufacturing. Carr and Meyer (1974) described the LOB technique in its present form. Arditi and Albulak (1986) applied LOB technique to a highway pavement construction project. Al Sarraj (1990) formalized the Line of Balance method and developed its first algorithms.

A computer program that can easily and effectively be used by contractors could improve construction productivity significantly. A number of tools that are based on the LOB principles were developed to deal with the scheduling of repetitive projects (Arditi et al., 2001a, Arditi et al., 2002, Tokdemir et al., 2006). Firat et al. (2009) developed a two-step approach to model-based scheduling using Advanced Line of Balance (ALOB) technique. Wang and Huang (1998) presented a new scheduling method called multistage linear scheduling based on the concept of a multistage decision process. Hegazy et al. (1993) presented an effort to enhance the capabilities of linear scheduling techniques, making them more practical and more attractive for use in construction. Lutz et al. (1994) modeled the impact of learning in their program while Arditi et al. (2001b) investigated the potential for formalizing the inclusion of learning effects into the LOB scheduling of repetitive unit construction. Finally, Harris and Ioannou (1998) created the repetitive scheduling model (RSM) that ensures continuous resource utilization.

A number of studies have been conducted to expand the standard features of linear scheduling methods. Resource management is one of these features. Minimizing project duration, while taking into account the constraints on resources, is a primary objective of resource allocation. On the other hand, resource leveling deals with minimizing fluctuations, peaks and valleys in resource utilization without changing project duration. All these sub-objectives and constraints can be considered within a global multi-objective resource-constrained scheduling problem. This is a combinatorial optimization problem with multiple and conflicting objectives, i.e., confine the daily resource usage within resource availability, finish the project as soon as possible, and make the resource histogram as smooth (leveled) as possible considering existing constraints (time and resource availability) and the degree of their "hardness" (Chassiakos and Kaiafa 2014).

Existing studies and methods for resource management in network (CPM) and linear schedules can be grouped into three categories: (1) analytical methods, (2) heuristic methods, and (3) meta-heuristic methods. The analytical methods may provide optimal and reliable solutions only for small problems but are not effective in large-scale problems such as typical or large-size construction projects. Various approaches have been formulated to solve the problem optimally including Integer Programming, branch-and-bound algorithms, and Dynamic Programming (Gavish and Pirkul 1991). Heuristic methods may perform well in simplified and recurrent problems but the solutions are quite case-dependent. A well-known heuristic algorithm is the minimum moment algorithm (Harris 1978). The objective in this algorithm is to minimize daily fluctuations in resource usage while keeping the total project duration unchanged. Meta-heuristic search mechanisms, mostly in the form of genetic algorithms, search for a population of solutions for the problem in preference to improving a single solution (Chen and Weng, 2009) being, thus, an intermediate solution technique between analytical and heuristic methods. Senouci and Eldin (2004) presented an augmented Lagrangian genetic algorithm model for resource scheduling. Hegazy (1999) employed a genetic algorithm to simultaneously analyze resource allocation and leveling. Chassiakos and Kaiafa (2014) presented a multi-objective resource allocation model for construction projects. Damsi et al. (2013a) developed a genetic algorithm-based resource leveling model for LOB schedules that does not impact productivity negatively. Damsi et al. (2013b) also developed a genetic algorithm based multi-resource leveling model for schedules that are established by the LOB.

Previous studies regarding resource allocation in repetitive projects have mainly focused on resource leveling or include restrictive simplifying assumptions which impede the realistic representation of actual construction projects. It is observed that other important objectives of the resource allocation problem, i.e.

the completion of the project within a given deadline or the confinement of the daily resource usage within resource availability are not considered all together. The aim of this work is then to develop an optimization method, based on the Line of Balance technique, for multi-objective resource-constrained scheduling of repetitive projects. The proposed method allows the consideration of the aforementioned sub-goals (along with the resource leveling objective) depending on the importance of each sub-goal, which is reflected by the corresponding weight in the objective function.

2. The Proposed Method

The resource-constrained scheduling and allocation problem involves three general conflicting objectives. The first refers to the confinement of the daily resource needs to existing availability constraints. The second involves the project duration minimization (or the achievement of a certain deadline) and is oppositely related to the previous one, i.e., as the number of available resources decreases, the project duration increases and vice versa. The third objective, which is rather independent from the other two, is related to the aim of utilizing a constant number of resources throughout the project or, equivalently, to develop a smooth (leveled) resource histogram. Real scheduling problems typically incorporate constraints regarding the resource availability and the desired project duration. These constraints may be "hard" (i.e., cannot be exceeded by any means) or "soft" (i.e., can be exceeded but at an additional cost, e.g., by recruiting additional resources). The proposed model is best suited to projects that display repetitive characteristics. It is based on the Line of Balance technique and aims to optimize specific parameters (project duration, resource availability, resource usage) in order to improve project management and reduce the total project cost.

The input data of the model include the project activities with their durations and precedence relationships, the required resources per activity, and the number of project units. The algorithm calculates the number of necessary crews and the time gap between the activities. Then, the production rate is calculated by the relationship:

$$R = \frac{C}{d} \tag{1}$$

where R is the production rate, C is the number of crews used in the activity, and d is the activity duration in one unit if one crew is used. The start time of the activity in the *i*th unit t_i is calculated by the following relationship:

$$t_i = t_1 + \frac{1}{R}(Q_i - 1) \tag{2}$$

where t_1 is the start time of the activity in the first unit, and Q_i is the number of units that have already been produced. The finish time of the activity in the *i*th unit can be calculated by adding the duration of the activity (d) to the start time of the *i*th unit.

The algorithm deployment for every schedule that is evaluated includes the following calculations:

1. The start and finish time of the first and last unit for each activity are calculated by (2) above.
2. A project schedule is developed based on the activity precedence relations and their durations. Activities may be scheduled at their early time or a bit later so that effective resource allocation solutions are searched.
3. The project duration is determined by the latest project activities.
4. The LOB diagram is calculated and is graphically presented for better result visualization.
5. The resource allocation histogram is developed and displayed.
6. The maximum and the average resource usage are calculated
7. The excess of the desired project duration and the resource over-allocation are recorded.

8. The degree of fluctuation of the resource histogram is recorded.

Several parameters for resource fluctuations were evaluated. Among them, the most indicative one seems to be the average deviation of the daily resource usage divided by the average resource value (this is considered as the resource leveling index).

Besides other inputs, the user inserts the problem constraints regarding time and resource availability. Considering that exceeding any of these constraints is associated with certain additional cost, the objective function of the proposed model is written as follows:

$$z = w_1 * PDE + w_2 * RAE + w_3 * RLI \quad (3)$$

where PDE is the project duration excess, RAE is the resource availability excess, and RLI is the resource leveling index. The first two terms assign a penalty for exceeding a given projects deadline or the available resource level while the third one penalizes the fluctuations in the resource histogram. Depending on the importance of each sub-objective (or, equivalently, the degree of "hardness" of the corresponding constraint), the weights w_i are adjusted to represent the cost associated with a unit deviation from the corresponding goal or constraint.

Due to the substantial number of alternative execution options, a genetic algorithm (GA) has been employed to search for optimal solutions. An array of size equal to twice the number of project activities is used as the basic chromosome and its content represents the number of crews for each activity and the gap between consecutive activities. The number of generations and other genetic operators are set dynamically depending on the problem characteristics. The application that is presented in the following section has been built through the Palisade Evolver ™ software which runs as an add-in of the Microsoft Excel ™. Appropriate data input and result forms have been developed in the form of Excel spreadsheets.

3. An Application Case Study

A 26-km long pipeline project is considered to illustrate the algorithm application (Damci 2013a). The project operations consist of seven activities that repeat themselves kilometer after kilometer throughout the project: (A) locating and clearing, (B) excavating, (C) laying aggregate, (D) laying pipes, (E) testing, (F) backfilling and (G) compacting. The information concerning the precedence relationships, the activity durations, the optimum crew size and the resource needs for each activity are presented in Table 1. Based on these inputs, the project duration is 65 days. The Line of Balance diagram and the resource histogram of the initial schedule are presented in Figure 1 and 2 respectively.

Table 1: Input data for case study project

Activity name	Number of crews	Number of workers in crew	Duration per unit (days)
(A) Locating and clearing	2	6	2
(B) Excavating	2	8	1
(C) Laying aggregate	3	10	1
(D) Laying pipes	2	7	1,5
(E) Testing	4	10	1
(F) Backfilling	5	6	2
(G) Compacting	2	9	2

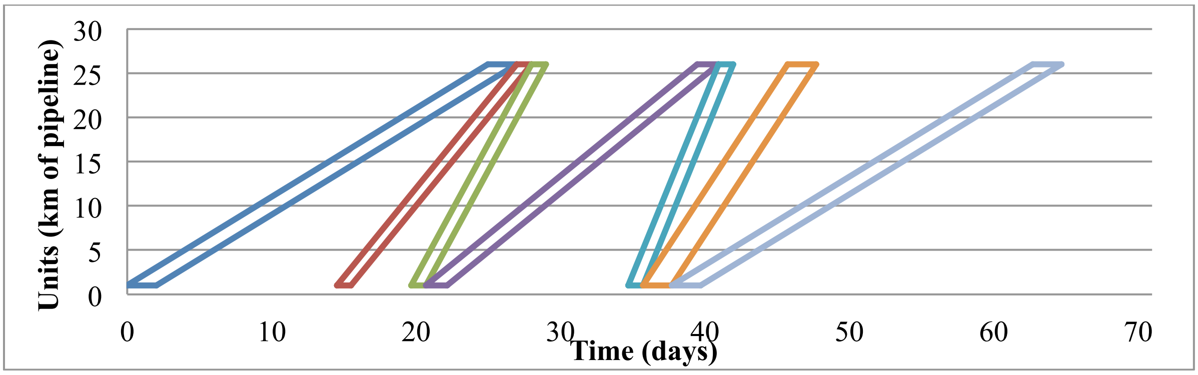

Figure 1: Initial scheduling Line of Balance diagram

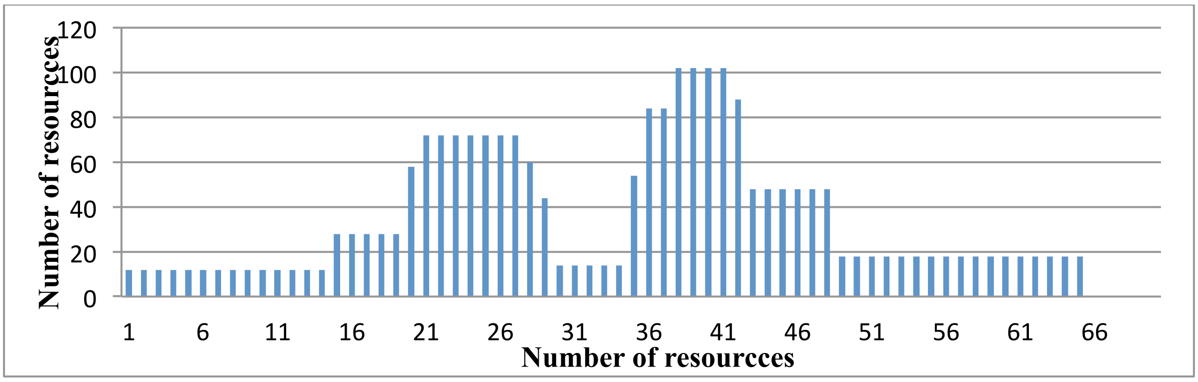

Figure 2: Initial resource histogram

Four scenarios are evaluated by properly adjusting the weighting parameters of the optimization function (3) to illustrate the algorithm flexibility and effectiveness to cope with different priorities and constraints. The first three scenarios focus on each specific optimization sub-goal individually while the fourth one analyzes a case in which all three sub-objectives are of comparable importance. In all cases, the (desirable) project duration is set to 50 days and the daily resource availability to 25 units. In each of the three single-objective scenarios, the weights of the other two objectives are not set equal to zero but are assigned a very low value in order to obtain the best result with regard to these secondary objectives after the major objective has been optimized.

The results are graphically presented in Figures 3 to 6 for the four scenarios respectively (only the resource histograms are presented due to space limitations). The values of the decision parameters in each case are quantified in Table 2. At first resource leveling was the only objective taken into account. Figure 3 indicates the resource histogram that is developed as a result of the resource leveling process. It is observed that a considerable amount of leveling has been achieved compared to the initial solution along with a large reduction in project duration. However, this is obtained at the expense of excessive daily resource requirement. The above analysis indicates that an initial project schedule is typically far away from being optimal.

Figures 4 and 5 present the resource histograms with regard to project duration and resource availability constraints (or objectives) respectively. Both of them satisfy the corresponding constraint. As expected, the less important constraint is not satisfied in either case. It is notable, however, that in the resource confinement scenario, the existence of the daily resource usage threshold leads to a highly leveled resource histogram (also shown in Table 2).

The last case with all sub-objectives present and with comparable importance leads to a resource histogram in which no constraint is fully satisfied but the deviations are moderate compared to the corresponding ones of the previous cases (Figure 6). The resource histogram is quite smooth while the project duration excess and the resource overload are not unaffordable. Clearly, many other solutions may be obtained if the parameter weights are further adjusted.

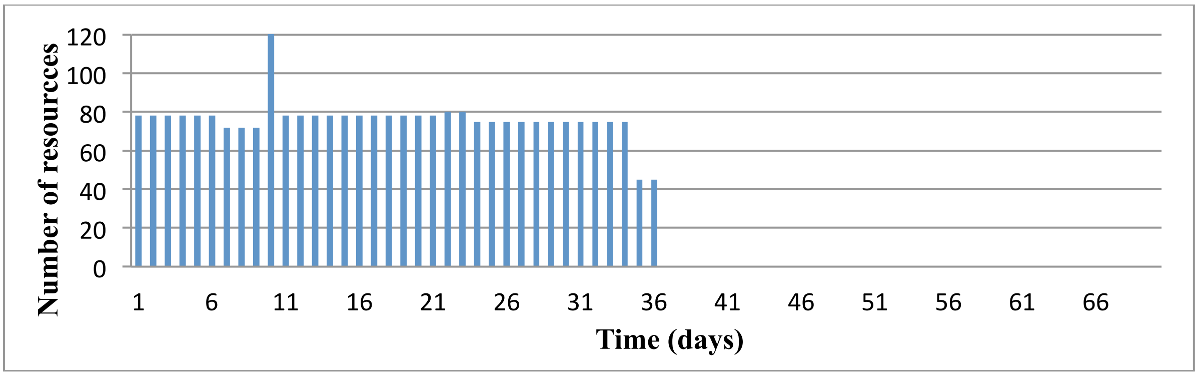

Figure 3: Resource histogram: resource leveling objective

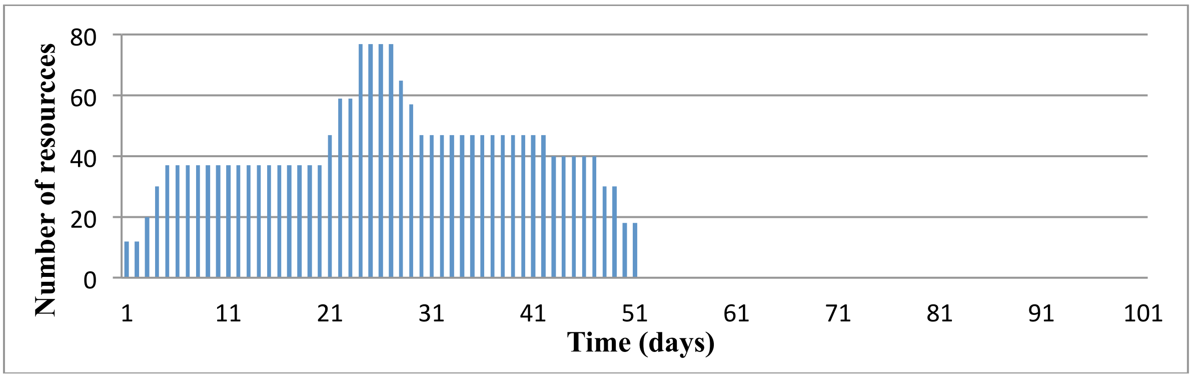

Figure 4: Resource histogram: project completion objective

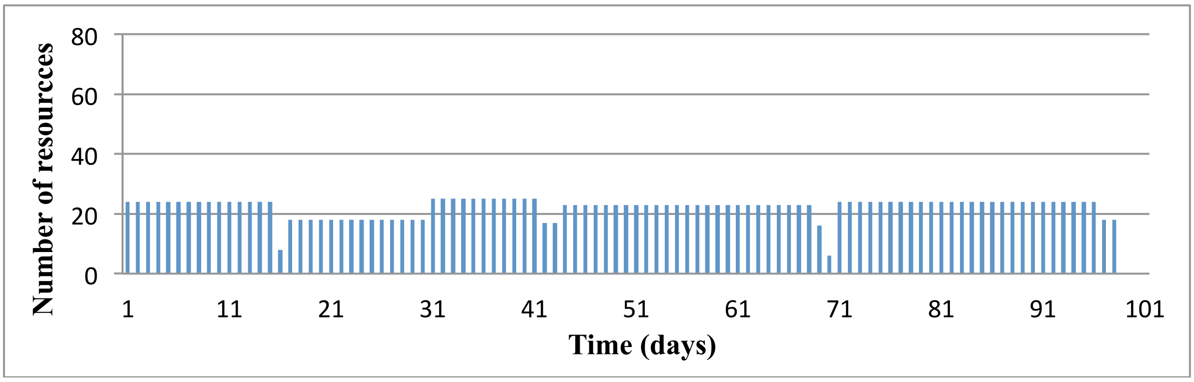

Figure 5: Resource histogram: resource confinement objective

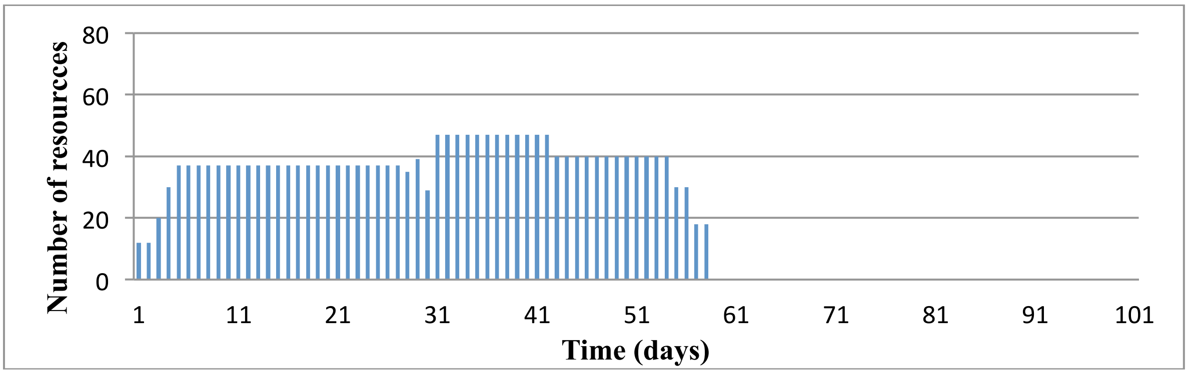

Figure 6: Resource histogram: all objectives simultaneously

Table 2: Case study result summary

Scenario No	0	1	2	3	4
Description	Initial scheduling	Resource leveling	Project deadline constraint	Resource availability constraint	All sub-objectives
Project duration	64,7	35,8	50,2	97,2	57,2
Average resource usage	36,3	76,1	42,5	22,3	37,4
Maximum resource usage	102	122	77	25	47
Project duration excess (PDE)	14,7	0	0,2	47,2	7,2
Average resource availability excess (RAE)	16,8	51,4	18,7	0	13,3
Resource leveling index (RLI)	0,68	0,06	0,25	0,11	0,14

4. Conclusion

The Line-of-Balance (LOB) method is a linear scheduling method which can be used for scheduling projects with repetitive characteristics such as highways, high-rise buildings, tunnels and pipelines. The main advantage of the LOB methodology is that it provides production rate and duration information in the form of an easily interpreted graphical form. The resource-constrained scheduling problem, on the other hand, has been studied over the past years mainly based on CPM scheduling but not as much for projects with repetitive characteristics. In this work, a LOB-based resource allocation model is developed aiming at optimizing all sub-objectives of the resource-constrained scheduling problem which are associated with resource leveling, finishing the project within a desirable duration, and confining the daily resource usage within resource availability. The proposed formulation leads to the minimization of the deviations of the decision parameters from their corresponding objectives or constraints coupled with comparative importance weights among competing objectives. Due to the problem size and complexity, a genetic algorithm has been employed to solve the optimization problem. The algorithm has been tested with data from a 26-km long pipeline project with seven activities. The results indicate the ability of the model to provide reasonable and targeted solutions with regard to the three resource allocation objectives depending on given priorities and weights. In conclusion, the LOB technique can be effectively used and provide reliable results for multi-objective resource-constrained scheduling of repetitive projects.

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