Resource Leveling of a Highway Project Using Branch and Bound Algorithm

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Abstract

The main purpose of this study is to level resource utilization of a 9.7 km long asphalt highway project using the branch and bound (B&B) algorithm. Since the highway project was highly linear and repetitive in nature, location-based planning (LBP) system was found to be appropriate for establishing the initial construction plan. In this study, the number of trucks utilized throughout the project was aimed to be leveled. Actual data of bill of quantities, resources (i.e., equipment), and production rates were obtained from the records of the contractor of this real-life highway project. Using these data, a location-based schedule was developed considering both resource and time constraints and precedence relations between activities via VICO Control (VC) software program. VC software provided the durations and the earliest start dates of the activities. Latest start dates were then manually calculated by making backward pass as it is the case in Critical Path Method (CPM). Having determined the earliest and latest start dates of the activities and precedence relationships between the activities, resource leveling problem was formulated as a binary integer mathematical program. In the mathematical formulation of the resource leveling problem, the objective function of minimizing the maximum daily resource usage was solved using B&B algorithm via Optimization Programming Language (OPL) software program considering the constraints of earliest and latest start dates of the activities and the precedence relationships between the activities. The leveled resource histogram was then compared with the initial resource histogram prepared based on the earliest start schedule.

Keywords: resource leveling, location-based planning, branch and bound algorithm, highway project

1 Introduction

Every construction project is distinctive and unique to itself due to the nature of construction industry. Not only locality, complexity and high production costs of construction industry products (i.e. buildings, airports, hospitals, coastal structures, etc.) but also production process factors such as weather conditions, procurement problems, and quality requirements create this uniqueness. Since every construction project is different, particular precautions and methods are required. This requisite increases the importance and necessity of proper construction management (CM) implementations. According to the Construction Management Association America (CMAA), construction management is a professional management practice consisting of an array of services applied to construction projects and programs through the planning, design, construction and post construction phases for achieving project objectives including the management of quality, cost, time and scope (CMAA, 2011). It appears that elements like “time, cost, quality and scope” are the fundamental performance indicators in a construction project. The primary focus of CM is to optimize these factors in order to complete a project successfully. The aforementioned optimization process consists of 4 major steps, which include planning, organization, management and control (Newitt, 2009). This order also represents the level of significance of these steps. Organization, management and control tasks for a project cannot be adequately fulfilled without a proper, rational and well-prepared plan.
In general, planning can be defined as a process of guiding all parties involved in a project from an idea to the completion in a satisfactory way (Adeli and Karim, 2001). This guidance makes planning essential, and even vital, for the construction industry, which is highly subject to uncertainties. Moreover, planning is the action of spreading activities over a pre-defined time period, while considering their not only durations but also resource and financial requirements. It can also be considered as a decision-making support tool prepared for controlling the work plan, detecting deviations from original program and reporting them to the owner/employer with their root causes. It is commonly acknowledged that the focus is on time when it comes to planning, scheduling and cost control processes. In this way, focusing only on the time brings such consequences as ignoring other important elements of the project objectives and the deterioration of the balance between them. The most important goal of planning is not only to consider all of the project elements together but also bring them into balance. Besides, making a good plan for construction is a tough task because, there are many ways and options to complete a project. Experiences can be useful while planning a construction project; however, due to the aforementioned uniqueness of each project, a new plan must be developed for every construction projects.

In developing a construction plan, it is common to adopt a primary emphasis on either cost control or schedule control (Hendrickson and Au, 1989). Some projects are primarily divided into expense categories with associated costs. In these cases, construction planning is either cost or expense oriented. Within the categories of expenditure, a distinction is made between costs incurred directly in the performance of an activity and indirectly for the accomplishment of the project. For example, borrowing expenses for project financing and overhead items are commonly treated as indirect costs. For other projects, scheduling of activities over time is critical in the planning process. In this case, the planner insures that the proper precedence relationships among activities are maintained and that efficient scheduling of the available resources is achieved. Traditional scheduling procedures emphasize the maintenance of task precedence (resulting in critical path scheduling procedures) or efficient use of resources over time (resulting in job shop scheduling procedures) (Hendrickson and Au, 1989). Finally, most complex projects require consideration of both cost and scheduling over time. In these cases, the integration of schedule and budget information is a major concern.

Effective and efficient use of resources is of utmost importance for successful construction management and thereby project planning. Another point to bear in mind is that, activity durations, which are critical during the planning process, are defined according to the availability of necessary resources to complete that task (Hinze, 2008). Major items of these resources include construction materials, labor, equipment, contractors, sub-contractors and money of course. In today’s world, resources are limited. Not taking resource limitations into consideration makes the plan estranged from the real world. On the other hand, considering resource limitations and planning resource flows makes plans not only more realistic but also easier to execute.

In general two different types of planning can be used in construction projects. These are activity-based planning (ABP) and location-based planning (LBP). In a project, each discrete work package is called activity (Callahan et al., 1992). ABP systems can be identified as more traditional approach to planning (Kenley, 2004). These systems focus on the unit of work to be done. Work is considered as the series of activities bonded each other only time-wise and activities are evaluated independent from the locations they occur. ABP tools, such as CPM (Critical Path Method) and PERT (Program Evaluation and Review Technique) have been dominantly preferred by construction management professionals and companies around the world since their emergence in the 1950’s. Through the years, as the construction projects have become more complex and the requirements of the industry have increased, these methods failed to meet the requirements. Some researchers have realized that CPM-based ABP methodology sacrifices efficient use of resources in favor of earliest completion (Arditi et al., 2002). Furthermore, it is known that ABP techniques are based on limitless resource assumption. It has been clearly seen that ABP techniques, which are not originally developed for the building industry but in the military/industrial environment, does not well match the characteristics of construction projects (Kenley and Seppänen, 2010).

In pursuit of better and more efficient management of resources, location-based planning (LBP) systems emerged as the answer. LBP provides optimum project time by smooth continuous flow of resources through locations (Kenley and Seppänen, 2010). Just like the relation between ABP and CPM, LBP depends on the fundamentals of Line-of-Balance (LoB) method. On the ground that construction projects are in repetitive nature (Lumsden, 1968), a linear scheduling system, which LBP can offer, is more suitable (Harris and Ioannau, 1998; Arditi et al., 2001). LBP is a resource-based management system tool for planning and controlling continuous workflow by both linear scheduling technique and leveled used of resources (Firat et al., 2009). Another important difference between ABP and LBP is that CPM identifies activity durations as input data whereas optimum activity durations are outputs of planning process of LBP. For each task, resource requirements and
quantities along with production rates are inserted as input data to LBP and activity durations are calculated (Kenley and Seppänen, 2010).

This research mainly aims to level resource utilization of a 9.7 km long asphalt highway project that was constructed in Sakarya using branch and bound (B&B) algorithm. In this study, the number of trucks utilized throughout the project was aimed to be leveled. Actual data of bill of quantities, resources (i.e., equipment), and production rates were obtained from the records of the contractor of this real life highway project.

2 Resource Leveling

Leveling is a kind of resource allocation, which aims to spread resource utilization rates throughout the schedule in order to achieve a uniform level of resource usage (Kenley and Seppänen, 2010). The main purpose of leveling process is to smooth the resource histogram, which means elimination of peaks and valleys in resource utilization histograms. Gordon and Tulip (1997) identify leveling cycle as a four-step process, which has to be repeated until all resources are allocated to activities:

- Schedule activities are of criticality.
- Find the most important activity within the remaining unscheduled activities.
- Schedule this activity in the most suitable time and place.
- Adjust the earliest and latest start dates of the remaining activities considering both the last scheduled activity and resource utilization impacts.

Besides, resource leveling also deals with resource over-allocation, which means that it is also the process that guarantees resource usage remains in available limits. Resource over-demand problems can be solved by several actions while using bar charts, such as (1) delaying the start of certain activities, (2) splitting task to satisfy resource limits, or (3) extending activity durations to reduce resource demands. However, one shortage of bar charts as a leveling tool is that they cannot display interdependencies between activities. Therefore, actions like delaying, splitting or extending activities are not possible due to the availability of precedence relations between activities. Accordingly, using algorithms and advanced planning techniques for such complicated issues may bring about better results. Furthermore, one of the most important facts about the leveling process is that project’s time limitations should also be considered along with resource constraints. Because it is important to keep total project completion time as it is, while dealing with resource utilization to create the most balanced and evenly distributed usage. If these actions create any changes in the completion duration of the project then it would be allocation not leveling. It should be kept in mind that leveling is changing activity orders in accordance with precedence relations in order to make resource usage rates leveled within the same total project time.

3 Research Methodology

The methodology of this study mainly involves the following steps:

- Review of the literature on not only planning and scheduling techniques but also resource management approaches,
- Obtaining actual data of a real life linear construction project that represent common properties and problems,
- Identification of linear activities and their resource utilization rates,
- Calculation of the production rates of each activity,
- Scheduling the project with location-based planning approach considering precedence relations and resource limitations,
- Implementation of the mathematical model prepared with binary integer programming (branch and bound algorithm),
- Verification and validation of the model.

Branch and bound (B&B) is a general algorithm for finding optimal solutions of various optimization problems, especially in discrete and combinatorial optimization. It consists of a systematic enumeration of all candidate solutions, where large subsets of fruitless candidates are discarded all together, by using upper and lower estimated bounds of the quantity being optimized.
4 Case Study

The studied case is a 9.7 km long asphalt highway construction project and was built in Sakarya, Turkey, in 2011. Width of the highway is 23 m for the first 8.4 km and 27 m for the remaining 1.3 km as it can be seen in Figure 1.

![Highway cross-sections](image)

4.1 Tasks and Quantities

The studied project consists of four different layers, which include: sub-base, plant-mix, binder and wearing. In addition to the production of these layers, drainage pipes were installed after the completion of the sub-base layer. Therefore, these tasks follow the order shown in Figure 2.
These layers are of various depths and the layer sections of the project are shown in Figure 3.

![Figure 3. Layer sections (a) in the first 8.4 km (b) in the remaining 1.3 km.](image)

Sub-base layer production took place only in the first 8.4 km of the project. Other layers, i.e., plant-mix, binder and wearing, along with the drainage pipes installation, were conducted throughout the entire project.

Since the project is highway construction, it is highly linear and repetitive in nature. The above-mentioned layers of the highway, along with the drainage, were constructed in the same order but with different quantities throughout the entire project. Quantities of the each task were calculated in detail, by taking the roof slope of the highway into consideration and total quantities of these activities are presented in Table 1.

**Table 1.** Total quantities of the asphalt highway construction works.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-base layer</td>
<td>39.000,00</td>
<td>m³</td>
</tr>
<tr>
<td>Drainage pipes</td>
<td>5.415,00</td>
<td>m</td>
</tr>
<tr>
<td>Plant-mix layer</td>
<td>30.500,00</td>
<td>m³</td>
</tr>
<tr>
<td>Binder layer</td>
<td>196.150,00</td>
<td>m²</td>
</tr>
<tr>
<td>Wearing layer</td>
<td>193.760,00</td>
<td>m²</td>
</tr>
</tbody>
</table>

**4.2 Location Breakdown Structure (LBS)**

For linear projects, especially for highway projects as in this case study, breaking entire work package down into locations, preferably mostly equal and continuous stations, improves the sharpness of the planning process and makes it a far easier objective to achieve. The project was conducted as sections of 500 m each and a location breakdown structure (LBS) was prepared in accordance with the actual data obtained from the real-life project as shown in Table 2. At the 18th location there are bridge construction works, therefore this location is limited with 20 m in order to contain only bridge works. Remaining distance was again divided into 500 m sections and last location, i.e., the 21th location, had the remaining 310 m part only.
4.3 Production Rates

Production rates for the activities differ since the numbers and productivities of the equipments and crews working on that task are different. Therefore, production rates of the activities were calculated separately based on the information taken from the company as shown in Table 3.

Table 3. Daily production rates of the activities.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Production Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-base layer</td>
<td>1,777.78 m$^3$/day</td>
</tr>
<tr>
<td>Drainage pipes</td>
<td>100 m/day</td>
</tr>
<tr>
<td>Plant-mix layer</td>
<td>1,684.21 m$^3$/day</td>
</tr>
<tr>
<td>Binder layer</td>
<td>8,333.33 m$^2$/day</td>
</tr>
<tr>
<td>Wearing layer</td>
<td>13,333.33 m$^2$/day</td>
</tr>
</tbody>
</table>

4.4 Precedence Relations

Activities follow the same production order for each location. For instance, in location 1, sub-base, drainage, plant-mix, binder and wearing productions are performed successively. They also follow the same sequence in the remaining locations. In order to understand the complete precedence relations between the activities and locations, laddering activities as shown in Figure 4 may be useful to visualize precedence relations better.
4.5 Calculation of the Early Start and Late Start Dates of the Activities

Using the actual data of bill of quantities, resources (i.e., equipment), production rates, and precedence relationships among activities obtained from the records of the contractor of this real life highway project, a location-based schedule was developed considering both resource and time constraints and precedence relations between activities via VICO Control (VC) software program. After all available data were loaded, VC produced activity durations and early start dates. After all of the early start dates were maintained, late start date of the last activity was taken equal to its early start time and late start times of all remaining activities were calculated manually by backward pass calculations using total floats as it is in CPM. In order to use total floats in backward pass, late start times of successor activities were taken into consideration for obtaining late start times of the predecessors. The late start times of the activities are calculated using the formula shown in Equation 1.

\[ LS_i = \min (ES_{j,L+1}; ES_{k,A+1}) - t_i \]  

(1)

Where \( LS_i \) is the late start time of the activity \( i \), \( t_i \) is the duration of the activity \( i \), \( ES_{j,L+1} \) is the late start time of the activity \( j \) within the same task but in the next location (activity order), and \( ES_{k,A+1} \) is the late start time of the activity \( k \) in the same location but the following task (location order).

In CPM, total float is the difference between the early and late start times of the activities. In accordance with the logic of CPM and LBP, activities with the same early and late start times, which means without total float (TF=0), are considered to be critical activities. As far as the calculations showed, 24 of total 101 activities (23.76\%) does not have total float and they are critical. Therefore, resource leveling model can work on the remaining 77 activities (76.24\%) for achieving model objectives. As an example, some of the activities’ early and late start times, durations and total floats are shown in Table 4.

<table>
<thead>
<tr>
<th>Activity No.</th>
<th>Activity Name</th>
<th>Location</th>
<th>Duration (day)</th>
<th>Early start time</th>
<th>Late start time</th>
<th>Total float (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sub-base layer</td>
<td>1</td>
<td>1.30</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>Sub-base layer</td>
<td>2</td>
<td>1.30</td>
<td>2.30</td>
<td>3.80</td>
<td>1.50</td>
</tr>
<tr>
<td>3</td>
<td>Sub-base layer</td>
<td>3</td>
<td>1.30</td>
<td>3.60</td>
<td>6.60</td>
<td>3.00</td>
</tr>
<tr>
<td>4</td>
<td>Sub-base layer</td>
<td>4</td>
<td>1.30</td>
<td>4.90</td>
<td>9.40</td>
<td>4.50</td>
</tr>
<tr>
<td>5</td>
<td>Sub-base layer</td>
<td>5</td>
<td>1.30</td>
<td>6.20</td>
<td>12.20</td>
<td>6.00</td>
</tr>
</tbody>
</table>

As seen in Table 4, calculated start dates are of decimal digits. However, decision variables should be continuous and integer numbers, therefore real numbers cannot be used in integer programming models. In order to be able to use data in integer programming models, all start dates and durations with decimal digits should be multiplied with 10 or its multiples. In this study, multiplying mentioned data with 10 was more than enough, since there was a maximum of one decimal digit among all data set.

4.6 Resource Leveling Process

In this study, the number of trucks utilized throughout the project was aimed to be leveled. In a resource leveling problem, several objective functions can be used. In this study, the objective function aiming to minimize the maximum daily resource usage (Wagner, 1964) was preferred. The mathematical formulation of this objective function is shown in Equation 2.

\[ Z = \min \{ \max (R_i) \} \]  

(2)

Where \( \min \) refers to minimization, \( \max \) denotes for maximum, and \( R_i \) refers to resources (i.e., trucks) required on day \( i \).

In order to use scheduling data in the branch and bound algorithm for resource leveling, the software named OPL (Optimization Programming Language) was used and the model was established for optimization. OPL is a
modeling tool used for solving different linear programming, integer programming and combinatorial optimization problems. It was originally developed by Pascal Van Hentenryck. It is a product of IBM and it provides a very easy user interface and efficient features (Hentenryck, 1999). OPL consists of expressive data structures and allows users to use specialized optimization algorithms. It is a combination of constraint logic programming and mathematical modeling languages; however it is not a universal programming language.

The proposed problem of resource leveling was formulated as a binary integer programming model. Before explaining this model, the explanations of the decision variables, which are the variables that give the solution to the problem, are given below. The start times of the activities are calculated using the formula presented in Equations 3 and 4.

\[ S_i = \sum_{t=ES_i}^{LS_i}(t, x_{it}) \quad \forall \ i \] (3)

\[ x_{it} = \begin{cases} 
1 & \text{if activity } i \text{ starts at time } t \\
0 & \text{otherwise} 
\end{cases} \] (4)

Where \( S_i \) is the start time of activity \( i \), \( ES_i \) is the earliest start date of activity \( i \) obtained from LBP, and \( LS_i \) is the latest start date of activity \( i \) calculated manually. This decision variable generates values for each activity, in each \( t \) time.

5 Findings

Resource histogram for the activities starting on earliest start dates is as shown in Figure 5. In this histogram, the maximum daily resource usage is 32 trucks.

As an example, the actual start times of some activities obtained after leveling trucks by the branch and bound algorithm are shown in Table 5.

![Figure 5. Resource histogram for the earliest start dates.](image)

<table>
<thead>
<tr>
<th>Activity No.</th>
<th>Activity Name</th>
<th>Location</th>
<th>Duration (day)</th>
<th>Early start time</th>
<th>Late start time</th>
<th>Actual start time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sub-base layer</td>
<td>1</td>
<td>1.30</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>Sub-base layer</td>
<td>2</td>
<td>1.30</td>
<td>2.30</td>
<td>3.80</td>
<td>2.30</td>
</tr>
<tr>
<td>3</td>
<td>Sub-base layer</td>
<td>3</td>
<td>1.30</td>
<td>3.60</td>
<td>6.60</td>
<td>4.10</td>
</tr>
<tr>
<td>4</td>
<td>Sub-base layer</td>
<td>4</td>
<td>1.30</td>
<td>4.90</td>
<td>9.40</td>
<td>6.70</td>
</tr>
<tr>
<td>5</td>
<td>Sub-base layer</td>
<td>4</td>
<td>1.30</td>
<td>6.20</td>
<td>12.20</td>
<td>9.50</td>
</tr>
</tbody>
</table>
Resource histogram obtained after leveling, in other words using the actual start times of the activities, is shown in Figure 6. In this histogram, the maximum daily resource usage is 24 trucks. An improvement of 33% was achieved.

![Figure 6. Resource histogram after leveling.](image_url)

6 Conclusions

This research proposed a mathematical model for leveling resources of a linear construction project, namely a highway construction project, scheduled with location-based planning technique. Mixed-integer programming with branch and bound algorithm was used to level resources. The objective was to minimize the maximum daily resource (i.e., trucks) usage. The leveling process brought about an improvement of 33%.

References