Using discrete-event simulation for process modeling: Case of work structuring of asphalt highway construction operations

G. Polat
Department of Civil Engineering, Istanbul Technical University, Maslak, Istanbul, Turkey

Y. Buyuksaracoglu
Polimeks Construction, Suzer Plaza, Sisli, Istanbul, Turkey

ABSTRACT: In this study, the resource planning problem of a real-life problem, namely a 4 km long and 14 m wide asphalt highway project, was handled. According to the contract between the owner and the contractor, all construction work should have been completed within 17 days. The contractor of this project aimed to determine the minimum number of resources required to complete the project within the estimated project duration and their utilization rates. In this research, this problem was handled using computer simulation technique. For this purpose, a dynamic, stochastic and discrete event simulation model was used. The simulation model was built using the ready-made simulation software Extend+BPR. The simulation results revealed that when 3 flagmen, 1 grader, 1 road roller, 1 water truck, 17 trucks, 1 paver, 1 rubber roller, 1 steel wheel roller, and 5 laborers are used, the construction phase of the project could be completed within 17 days. Among all the resources required to complete the project, while the rubber roller had the maximum utilization rate (68%), the water truck had the minimum value (7%). The simulation results also indicated that while any increase in the number of these resources did not help to shorten the project duration, any decrease in the number of these resources brought about severe delays. Although the proposed methodology has some limitations, it has great potential to optimize resources and production rates in similar asphalt highway construction operations, especially when used during the planning phase.

1 INTRODUCTION

Peter Drucker called the automotive industry “the industry of the industries” in 1946. Indeed, a great number of new production and management philosophies first emerged in the automotive industry and then they diffused into other industries. Lean production is one of those philosophies. Lean production philosophy was first introduced by Toyota Motor Company. Briefly, lean production aims at the ideal of 100% value-added work with zero or minimum waste (Womack et al. 1990, Koskela 1992, Koskela 1997). The automotive industry is now using half the manufacturing space, half the human effort in factory, half the product development time, and half the investments in tools because of the successful implementation of lean production concepts (Womack et al. 1990). After Toyota Motor Company’s great triumph, lean production principles were then rapidly employed by other automotive companies as well as other industrial sectors (Gann 1996).

Construction is not different from other industries. Lauri Koskela published a seminal report in 1992 on the applicability of lean production concepts in the construction industry (Koskela 1992). Since then, numerous construction academics and professionals have begun to seek ways to employ lean production principles in the construction industry and thereby deliver better value to construction owners. All those endeavors are known as “Lean Construction” (e.g., Ballard & Howell 1998, Bertelsen & Koskela 2002, Koskela & Howell 2002). The Lean Construction Institute (LCI) was founded in 1997 in order to develop knowledge regarding project based production management in the design, engineering, and construction of capital facilities (LCI 2004). LCI (2004) defined lean construction as a production management-based approach to project delivery - a new way to design and build capital facilities. Lean Construction suggests designing a product and its production process concurrently, structuring work throughout the project phases to maximize value and to reduce waste at the project delivery level, improving total project performance rather than just reducing the cost or increasing the speed of any activity, using a conformance-based vs. a deviation-based performance control strategy, and improving the reliability of work flow among specialists in design, supply and assembly (LCI 2004).

Glenn Ballard, the co-founder of LCI, introduced the Lean Project Delivery System (LPDS) as a guide for successful implementation of lean production principles in construction (Ballard 2000). Figure 1 represents the basic elements of LPDS.

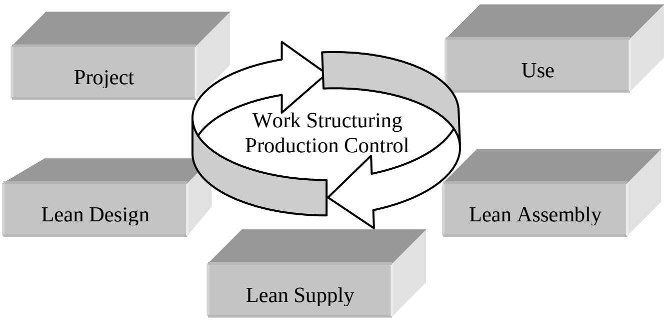

Figure 1. Lean project delivery system (LPDS) (Abdelhamid 2003)

As seen in Figure 1, work structuring plays a critical role in LPDS. LCI (2004) defines work structuring as the "process of breaking work into pieces, where pieces will likely be different from one production unit to the next, so as to promote flow and throughput". Ballard (2000) suggests that the process design should be developed in alignment with product design, the structure of supply chains, the allocation of resources, and design-for-assembly efforts. According to Ballard (2000), the main goal of work structuring is to make work flow more reliable and quick while delivering value to the customer.

Several tools and techniques have been used for work structuring. One of those techniques is the computer simulation of construction operations. Computer simulation ensures more realistic structuring and planning of construction operations as it allows for observing technological and logical dependences and resource availability limits, and analyzing the impacts of potential variations on the total project performance. Simulation has been used in construction management as a planning and scheduling technique since the 1970s. Simulation is superior to other planning and scheduling techniques as it provides a true representation of the output behavior (Ammar & Mohieldin 2002).

In this study, the resource planning problem of a 4 km long and 14 m wide highway project was handled using computer simulation technique. In order to solve the problem of optimizing resources, a dynamic, stochastic and discrete event simulation model was built using the ready-made simulation software Extend+BPR.

2 COMPUTER SIMULATION OF CONSTRUCTION OPERATIONS

Simulation is defined as the art and science of designing a model that acts in the same way as a real system does (Law & Kelton 2000). Simulation provides a virtual world where decision makers can better understand the complex nature of the problem by conducting experiments in a more controllable and low-cost environment (Wang & Halpin 2004). The basic advantages of simulation are its generality, flexibility and power of simulating almost any behavior of the real system (Martinez & Ioannou 1997). Computer simulation has been successfully used to analyze complex systems in operations-research and in the manufacturing industry.

Simulation makes more sense when the real system has the following characteristics (Al-Sudairi 2000):

- High volume of transactions,
- Complex flow patterns,
- Complex process and business rules,
- Delays, waits and queues,
- Synchronized parallel processing,
- Dramatic changes to workflow,
- Many process variables.

Since construction operations have all the above-mentioned characteristics and are predominantly affected by uncertainties and governed by technological and logical dependences, simulation can be effectively used to model and thereby analyze the performance of these operations (e.g., Wang & Halpin 2004). Construction project planners often use computer simulation to predict the performance of construction operations in terms of process flows and resources utilization (Cheng & Feng 2003). In many instances, the performance of a construction operation is subject to the structure of supply chains and the allocation of resources.

Simulation has been successfully used in a large variety of fields in construction management such as productivity measurement (e.g., Zayed & Halpin 2001), resource management (e.g., Hassan & Gruber 2008), scenario-based project performance evaluation and improvement (e.g., Lu & AbouRizk 2000, Polat & Arditi 2005, Polat et al. 2006, Polat 2009), site planning (e.g., Tantisevi & Akinci 2008), etc.

In the construction area, there are several bespoke simulation packages that are specially designed for modeling construction operations such as HOCUS, CYCLONE, INSIGHT, RESQUE, UM-CYCLONE, Micro-CYCLONE, COOPS, Web CYCLONE, CIPROS, DISCO, STROBOSCOPE, SYMPHONY, SIREN, STEPS, PICASSO, COST, etc. (e.g., Ammar & Mohieldin 2002, Cheng & Feng 2003). In addition to those bespoke simulation packages, some commercial simulation software packages such as Extend+BPR, Arena, etc. are also commonly used to model the applications in construction (e.g., Abdulhadi 1997, Al-Sudairi 2000, Polat & Arditi 2005, Polat et al. 2006, Polat 2009).

3 CLASSIFICATION OF SIMULATION

There are three common approaches to classify simulation, which are (Law & Kelton 2000):

- Static vs. Dynamic Simulation Models: While static simulation does not contain time factor, dynamic simulation evolves over time (Shi 2001). Both static and dynamic simulation consists of two major phases, i.e., designing a mathematical logical method of a real system and experimenting this model on a computer (Pritsker 1995).
- Deterministic vs. Stochastic Simulation Models: Deterministic simulation models do not contain any probabilistic inputs and the results are fully determined as long as the inputs are given (Law & Kelton 2000, Shi 2001). On the other hand, in real life, most of the components of the systems are random (probabilistic). If a simulation model contains variables defined by a random distribution function, it is called a stochastic model. Stochastic models produce output that is itself random. Therefore, the inputs should reflect the characteristics of the real system (Law & Kelton 2000, Shi 2001).
- Continuous vs. Discrete Simulation Models: While continuous simulation is used to model systems whose conditions and dependent variables change continuously with respect to time, discrete-event simulation is used to model systems whose conditions and dependent variables discretely change at specified points in time as a result of specific events (Pritsker 1995, Al-Sudairi 2000, Law & Kelton 2000, Shi 2001).

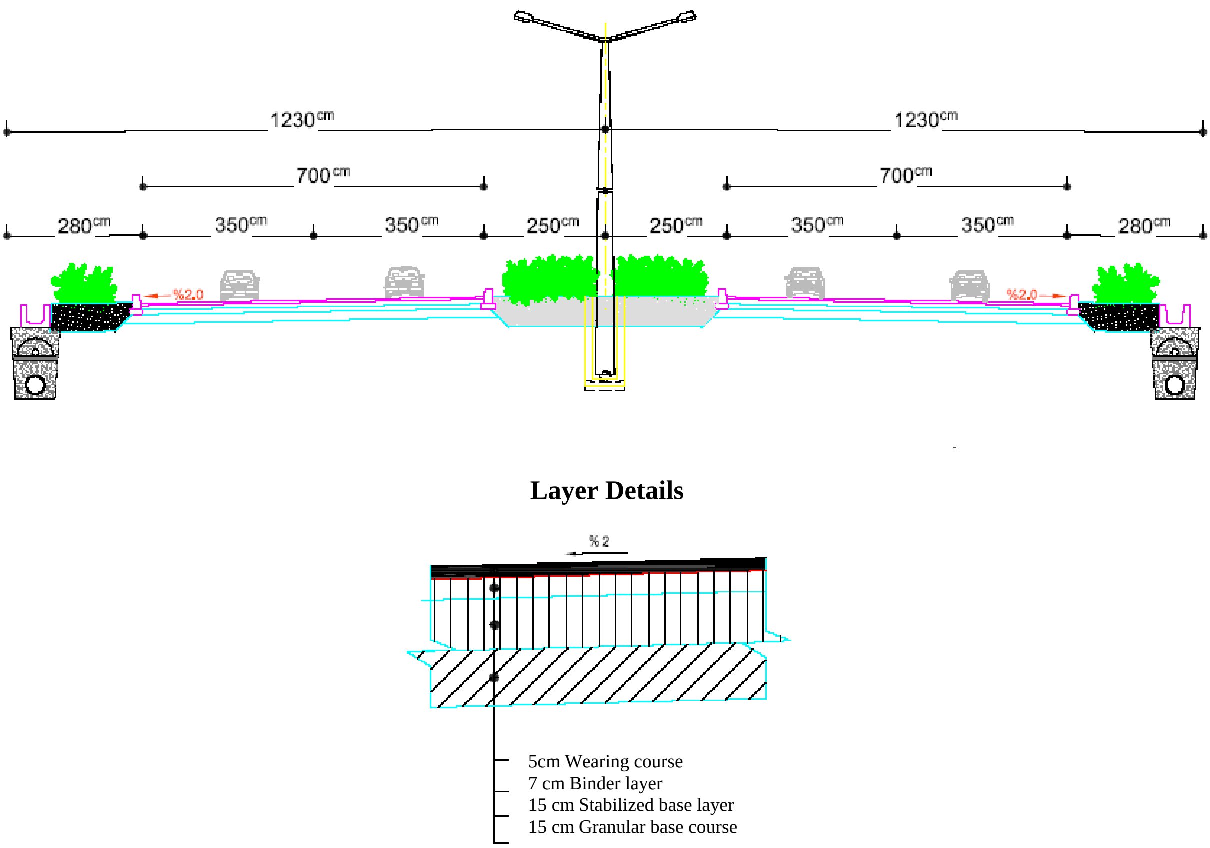

Figure 2. Details of the studied highway project.

4 DISCRETE EVENT SIMULATION MODELING FOR WORK STRUCTURING: ASPHALT HIGHWAY CONSTRUCTION OPERATIONS

Linear construction projects, e.g., highways, tunnels, high-rise buildings, bridges, pipeline networks, etc., typically consist of several repetitive activities and operations, which mainly utilize the same resources. The reliability of the work flow in a linear construction project is mostly subject to the extent to which those resources are efficiently and effectively planned and managed. Thus, resource planning and management play a significant role in the successful implementation of these projects. It is commonly claimed that traditional scheduling techniques, e.g., CPM or PERT, are inadequate to solve resource allocation problems of linear construction projects as the technological and logical constraints on the resources and the availability of the resources when needed cannot be clearly observed. Asphalt highway construction is a good example for a linear construction project. It consists of several similar or identical activities which are repetitive in nature.

In this study, the resource planning problem of a 4 km long and 14 m wide highway project, whose details are shown in Figure 2, is handled. According to the contract between the owner and the contractor, all construction work should be completed within 17 days. The contractor aims to determine the minimum number of resources required to complete

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This problem is handled using computer simulation technique. In this research, a dynamic, stochastic and discrete event simulation model is used. The developed simulation model is dynamic because some inputs of the model evolve over time due to the stochastic and changeable nature of the asphalt highway construction operations.

In order to provide the simulation model with the dynamic feature, an interface with an MS Excel file was created, which represents the changes in some of the inputs of the model over time. Discrete-event simulation is used to model the work structuring of asphalt highway construction operations as the conditions and dependent variables discretely change at specified points in time. The simulation model was built using the ready-made simulation software Extend+BPR.

According to AbouRizk & Halpin (1992), beta distribution is appropriate for representing construction activity durations. The beta distribution can be best approximated with a triangular distribution, which requires three parameters for its definition: the low-
This program was chosen because of its powerful features including high flexibility, great capacity, animation capability, and sophisticated graphical user interface. Abdulhadi (1997), Al-Sudairi (2000), Polat & Arditi (2005), Polat et al. (2006), and Polat (2009) have used Extend+BPR in similar studies with great success.

The asphalt highway construction operations mainly consist of four consecutive steps, which include; (1) the placement and compaction of granular materials to form the granular base course (see Fig. 3), (2) the placement and compaction of hydrated granular materials to form the stabilized base layer

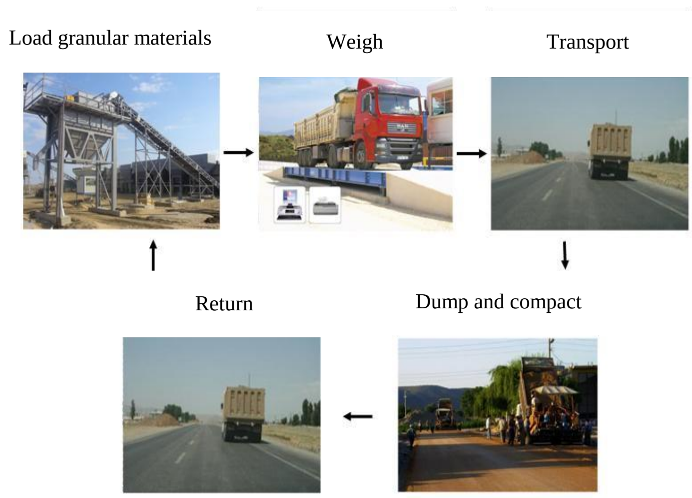


Figure 3. DE simulation model for road granular base course construction

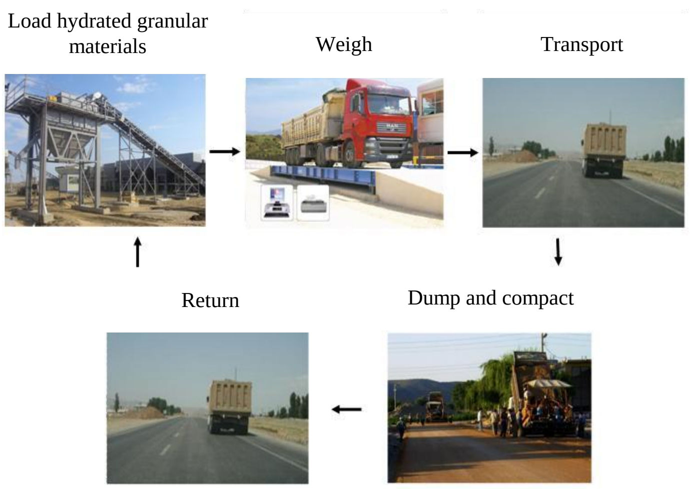
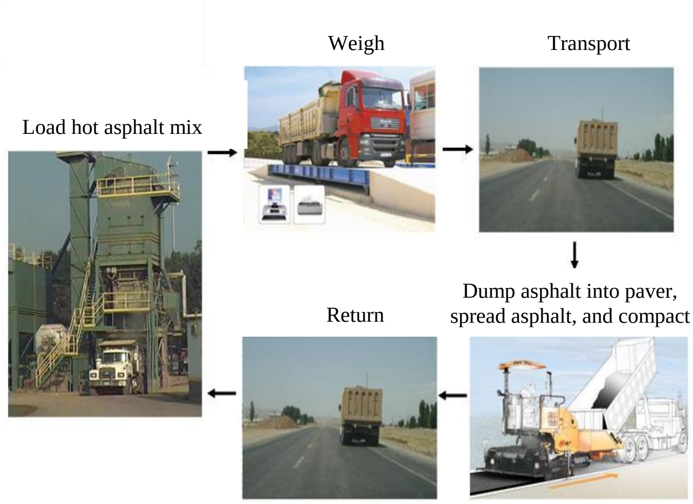


Figure 4. DE simulation model for stabilized base layer construction



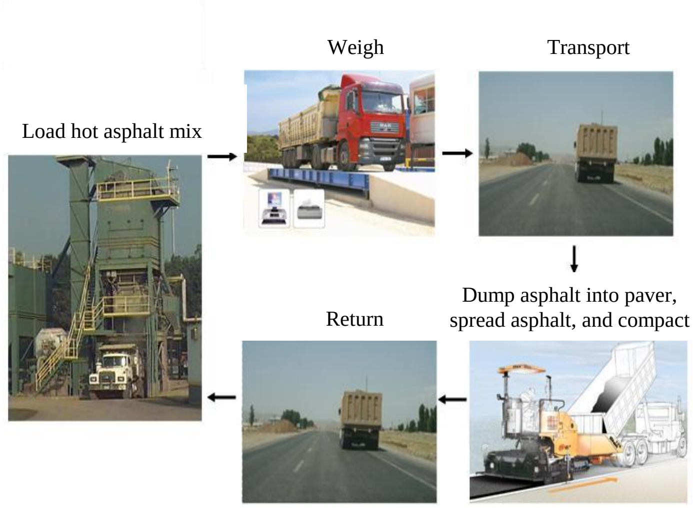


Figure 6. DE simulation model for wearing course construction

Figure 6. DE simulation model for wearing course construction

er or optimistic limit, the mode or most likely value, and the upper or pessimist limit (McCabe 2003). Therefore, the triangular distribution was used to represent the random factors inherent in the durations of the activities associated with highway construction operations. Table 1 shows the minimum, maximum, and most likely duration values of the operations associated with road granular base course construction, which are obtained from similar projects previously completed by the contractor.

Table 2 shows the quantity take-offs estimated for the highway project to be constructed.

Resources that are required to carry out the above-mentioned operations for the 4 km long and 14 m wide highway project and their capacities are shown in Table 3. It should be noted that the capacity values are obtained from similar projects previously completed by the contractor.

Table 1: Activity duration values for road granular base course construction

Parameter	Duration of each activity (in minutes)					
	Load	Weigh	Transport	Dump and Compact	Return	Total Duration
Minimum value	6	2	17	4	15	44
Maximum value	8	3	19	6	17	53
Most likely	7	2.5	18	5	16	48.5

Table 2: Quantity take-offs

Layer	Height (m)	Length (m)	Width (m)	Density (Ton/m^3)	Quantity (Ton)
Granular base course	0.15	4,000	14	1.80	15,120
Stabilized base layer	0.15	4,000	14	2.10	17,640
Binder layer	0.07	4,000	14	2.40	9,408
Wearing course	0.05	4,000	14	2.40	6,720

Table 3: Resources used in the construction of each layer and their capacities

Layer	Required Resource	Capacity Values	Distribution Function
Granular base course	Truck	24-26 tons	Triangular
Granular base course	Grader	2900-3200 tons/day	Triangular
Granular base course	Water truck	8-12 mins/hour	Triangular
Granular base course	Road roller	2900-3200 tons/day	Triangular
Granular base course	Flagman	6.5-7.5 hours/day	Triangular
Stabilized base layer	Truck	24-26 tons	Triangular
Stabilized base layer	Paver	6.25-8.33 tons/min	Triangular
Stabilized base layer	Road roller	6.5-7.5 hours/day	Triangular
Stabilized base layer	Rubber roller	6.5-7.5 hours/day	Triangular
Stabilized base layer	Water truck	8-12 mins/hour	Triangular
Stabilized base layer	Flagman	6-8 hours/day	Triangular
Binder layer	Truck	24-26 tons	Triangular
Binder layer	Paver	4.2-6.25 tons/min	Triangular
Binder layer	Steel wheel roller	6-8 hours/day	Triangular
Binder layer	Rubber roller	6-8 hours/day	Triangular
Binder layer	Laborer	4-6 hours/day	Triangular
Binder layer	Flagman	4-6 hours/day	Triangular
Wearing course	Truck	24-26 tons	Triangular
Wearing course	Paver	4.2-6.25 tons/min	Triangular
Wearing course	Steel wheel roller	6-8 hours/day	Triangular
Wearing course	Rubber roller	6-8 hours/day	Triangular
Wearing course	Laborer	4.5-7 hours/day	Triangular
Wearing course	Flagman	4.5-7 hours/day	Triangular

In this project, it is planned that four consecutive processes will be carried out on a daily basis. According to this plan, on the first day of the project, granular materials will be placed on one section and compacted to form the road granular base course, on the second day, hydrated granular materials will be placed on the constructed road granular base course section and compacted to form the stabilized base layer, on the third day, the hot asphalt mix will be placed on the stabilized base layer and compacted to form the binder layer, and then on the fourth day of the project, the hot asphalt mix will be placed on the binder layer and compacted to form the wearing course. These consecutive processes will be repeated until the 4 km long and 14 m wide highway project ends. Asphalt highway construction operations are cyclic and linear processes, and as seen in Table 3, most of them utilize the same resources. Thus, technological and logical dependences and the resource availabilities, especially for the operations which use the same resources need to be considered when designing the process.

Table 4 shows the minimum number of resources required to complete the project within the estimated duration and their utilization rates. The simulation results revealed that when 3 flagmen, 1 grader, 1 road roller, 1 water truck, 17 trucks, 1 paver, 1 rubber roller, 1 steel wheel roller, and 5 laborers are used, the construction phase of the project can be completed within 17 days.

Table 4: Minimum number of resources needed to complete the project and their utilization rates

Resource	Quantity	Utilization Rate
Flagman	3	31%
Grader	1	24%
Road roller	1	50%
Water truck	1	7%
Truck	17	29%
Paver	1	56%
Rubber roller	1	68%
Steel wheel roller	1	42%
Laborer	5	32%
Total Project Duration: 17 days		

The simulation results indicated that while the rubber roller has the maximum utilization rate (68%), the water truck has the minimum value (7%). This finding is reasonable as the rubber roller is used in the placement and compaction of three layers, namely stabilized base layer, binder layer, and wearing course. On the other hand, water truck is used in the construction of two layers, i.e., granular base course and stabilized base layer, and moreover, it is not used constantly. The water truck is only used to moisture the placed materials. According to the site records obtained from previous similar projects completed by the contractor, the water truck is used for only 8-12 minutes every hour (see Table 3). Therefore, it is reasonable that its utilization rate throughout the project is very low.

The simulation results also revealed that while any increase in the number of these resources does not help to shorten the project duration, any decrease in the number of these resources brings about severe delays. For instance, employing 2 flagmen rather than 3 flagmen brings about one day delay.

A special concern in asphalt highway construction operations is that the operations at the asphalt plant and the paving works on the site should be coordinated. Early asphalt truck arrivals may lead to trucks waiting on the site, possibly causing the asphalt temperature to drop below the minimum requirement for paving, which is normally around 135°C. On the other hand, site-paving operations may be interrupted due to late asphalt truck delivery.

The developed simulation model enables users to determine the arrival times of asphalt trucks that ensure continuous site operations. As an example, Table 5 shows arrival times of the first ten asphalt trucks used in the construction of binder layer. The results fit closely with actual site records

Table 5: Arrival times of the first ten asphalt trucks used in the construction of binder layer

Truck Identification	Truck Arrival Time (minutes after starting paving)
1	0.00
2	7.48
3	14.62
4	21.27
5	28.30
6	35.60
7	42.18
8	50.03
9	56.97
10	64.57

5 CONCLUSIONS

Work structuring is defined as the “process of breaking work into pieces, where pieces will likely be different from one production unit to the next, so as to promote flow and throughput”. Several tools and techniques have been used for work structuring. One of those techniques is the computer simulation of construction operations. Simulation has been widely used in construction management as a planning and scheduling technique since the 1970s. Simulation is superior to other planning and scheduling techniques as it provides a true representation of the output behavior. In the construction area, bespoke simulation packages that are specially designed for applications in construction projects are used to model construction operations as well as commercial simulation software packages.

In this study, the resource planning problem of a 4 km long and 14 m wide highway project was handled. According to the contract between the owner and the contractor, all construction work should have been completed within 17 days. The contractor aimed to determine the minimum number of resources needed to complete the project within the estimated project duration and their utilization rates. The main objective of this research was to solve resource planning problem using computer simulation technique. For this purpose, a dynamic, stochastic and discrete event simulation model was used. The simulation model was built using the ready-made simulation software Extend+BPR.

Asphalt highway construction operations are cyclic and linear processes and most of the operations utilize the same resources. Thus, technological and logical dependences and the resource availabilities, especially for the operations which use the same resources needed to be considered when designing the process.

The simulation results revealed that when 3 flagmen, 1 grader, 1 road roller, 1 water truck, 17 trucks, 1 paver, 1 rubber roller, 1 steel wheel roller, and 5 laborers are used, the construction phase of the project can be completed within the estimated project duration, namely 17 days. While the rubber roller has the maximum utilization rate (68%), the water truck has the minimum value (7%). The simulation results also indicated that while any increase in the number of these resources does not help to shorten the project duration, any decrease in the number of these resources brings about severe delays. The developed simulation model enables users to determine the arrival times of asphalt trucks that ensure continuous site operations.

Although the presented simulation model is simplistic and limited as it is based on several assumptions, it has great potential to optimize resources and production rates in similar asphalt highway construction operations, especially when used during the planning phase.

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