Construction Productivity Simulation Analysis:

Asphalt Paving Operation Case Study

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***Abstract*— Construction project success is usually measured in terms of cost and time efficiencies. For highway construction in particular, time efficiency is very critical, given the traffic delays and higher accidents risks associated with highway construction zones. This research is focused on analyzing productivity and time and cost efficiency at the construction process level rather than the contractual, procurement, or project scheduling aspects of highway construction management. A detailed examination of the asphalt paving process is presented. The asphalt paving process is analyzed utilizing computer simulation to identify potential improvement to reduce its duration. A sensitivity analysis is conducted to evaluate different alternatives. This research focus is identifying areas of potential changes in the asphalt pavement construction processes that could lead to reduce construction project times without cost increases.**

***Keywords*— construction simulation, productivity, asphalt paving, sensitivity analysis**

I. Introduction

Several studies have been conducted on determining contract times and reducing project times through contractual means [1], [2], and [3]. These studies have focused on the contractual and scheduling aspect of the issue. Various accomplishments on some highway construction projects have also suggested that project construction time can be reduced through use of innovative construction methods, materials, or equipment, such as pre-cast box culvert [4], concrete pavement, asphalt paving [5], experimental products and equipment [6], etc.

In addition to duration analysis, an in-depth study of these innovative methods would be necessary, through constructability reviews. Previous studies on constructability reviews include a study by the Construction Industry Institute (CII), Wisconsin DOT, and also by Indiana DOT [7]. The major issue to be addressed in this research project is identifying areas of potential changes in a typical asphalt pavement construction process that could lead to reduce construction project times. Identifying potential changes in the process could reduce highway construction times and hence minimize road closures and risks associated with highway construction zones. The focus of this study is an asphalt paving process utilizing a paving machine, rollers, and 20 tons capacity tri-axle trucks. The objectives of this research study can be summarized as follows: Examine a typical asphalt paving construction process; analyze the process using computer simulation; and identify potential improvements to the process to reduce its duration.

II. Background

A. *Construction Simulation*

Construction computer simulation is a valuable construction analysis tool that is well suited to the study of resource-driven processes. It provides the analyst insights into resource (labor, equipment, and materials) interaction, and assists in identifying which factors are important. Simulation allows the modeler to experiment with and evaluate different scenarios. Normally, such experimentation and study would be too costly to be carried out in the real world [8], [9], and [10]. With the emergence of the desktop computer, application of computational methods has become more accessible. In particular, simulation of construction processes to establish anticipated levels of production and solve some of the problems related to the randomness of construction operations has become a more widely accepted analysis tool.

For this research, the MicroCYCLONE computer simulation program was used. MicroCYCLONE is a microcomputer based simulation program designed specially for modeling and analyzing site level processes that are cyclic or repetitive in nature. In broader terms, it can be used to model construction operations that involve the interaction of tasks with their related duration, and the resource unit flow routes through the work tasks are the basic rationale for the modeling of construction operations. MicroCYCLONE is based on classical networking techniques. It uses the network modeling concepts of Cyclic Operations Network (CYCLONE). The CYCLONE approach provides a graphical format in terms of which the process of interest can be defined and solved using simulation techniques.

B. *Asphalt Paving Operation*

Asphalt paving is the most common process of highway construction. Asphalt is used for paving because of its adhesive and waterproofing properties.

Asphalt was used in 3800 B.C. in the Euphrates and 2500 B.C. in Egypt. The Sumerians used asphalt in 6000 B.C. for its shipbuilding industry. Today, asphalt is applied to roofing, sealants, caulking, brake linings, paints, enamels, and most widely used in the highway paving industry [11]. The asphalt paving process involves many sub-processes described as follows:

1) Batch Plant Production

Asphalt is usually manufactured in plants away from job sites. First, aggregate travels through the cold feed bins, where initial proportioning of the aggregate takes place. The quantity of material leaving each bin is regulated by the size of the gate opening, or the speed of a belt, or a combination of the two. The aggregate is sent to a drier. Here the moisture is removed and is heated to provide the proper mixing temperature in the pugmill. The aggregate continues to the hot elevator by screens to the hot bins. The screens provide the final separation of the aggregate [12]. The different sizes of aggregate are released into the weight hopper one bin at a time. The aggregate is dropped into the pugmill for mixing with the asphalt. The mixture is then dropped into a waiting truck or moved to a storage silo. Samples are taken from each hot bin for testing. A sieve analysis is conducted as well as gradation test. From the gradation information, the weight of the aggregate must be equal to the design gradation. A trial run should be performed and the weights adjusted until the desired mix is produced.

2) Paving Process

Before the paving operation starts, an asphalt distributor is used to spray asphalt on the unpaved surface. This film of asphalt serves as the prime and tact coats. The coats are then allowed to cure before the actual paving resume. The purpose of having these coats is to prevent any slippage between the surface and overlay during or after the compaction [13]. To start the paving operation, the paver (spreader) is positioned properly onto the road. The screed of the paver is lowered onto block of the same depth of the loose asphalt mat that is going to be laid on the road. The screed function is setting the depth of the asphalt mix. After that, the block can be removed and paving can start. As soon as the haul truck arrives at the job site, the paving inspector must check that the asphalt delivered must be in a satisfactory condition. If asphalt condition is not acceptable, the mix will be sent back to the batch plant to be reprocessed. After all conditions are satisfied, the haul truck can load the mix into the receiving hopper of the paver. When loading the mix into the receiving hopper, the haul truck is placed carefully in front of the paver. The rear wheels of the truck should be in contact with the truck roller of the paver to avoid any misalignment with the paver. The paver will push the truck forwards as it paves the road. If skewness happens, the whole process will be delayed because they have to reposition the truck in front of the paver [13].

As soon as the first load of asphalt mix has been spread, the uniformity of the asphalt texture should be checked. Operators will adjust the appropriate adjustment points to correct any non-uniformity. Any segregation of materials also should not be allowed. Operation should be stopped immediately if any segregation is detected. The operators should also be aware of is the crown control. Pavement with crown has to be redone all over again. In addition to that, operators should continuously loosen the mix that clings to the sides of the hopper and push it back into the active mix. If the asphalt mix grows cold, it cannot be properly compacted and thus, looses its strength. The last process of paving is compaction. This process is highly influenced by major mix proportion; asphalt content, aggregate size, filler content, and mix temperature. Appropriate rollers and rolling methods should be used in accordance with these proportions. Rollers should be moved in a slow but uniform speed to achieve the best result. These rollers should also be in good conditions. Any irregularities in the rollers' performance will result in poor compaction of the asphalt; thus, the pavement will be less durable. The rollers should not reverse suddenly while compacting because this action can displace the mix. If displacement happens, the whole mat should be loosened with lutes or rakes and restored to the original grade before rolling can restart [13].

The lack of density during construction of asphalt causes many problems. It is necessary to obtain high density to insure that the asphalt will provide the necessary stability and durability. For instance, low density generally causes long-term deterioration when the asphalt begins cracking. Therefore various methods have been used to measure the asphalt density. Proper aggregate gradation and asphalt content are important parameters to ensure that the density of asphalt meets the requirement. Generally, poor gradation results in a reduction of voids in the mixture; thus, reduces the asphalt content, which serves as the lubricant for aggregates in the mix. The stiff mix is more difficult to compact. Both the aggregate gradation and the asphalt content are interrelated and equally important [13].

III. Asphalt Paving Case Study

The focus of this research is to analyze an asphalt paving process utilizing a paving machine, rollers, and 20 tons capacity tri-axle trucks, together with the construction crew. The asphalt paving operation in that case study project was examined, monitored, modeled, and analyzed in order to identify ways to reduce its duration. Asphalt paving process is a linear process that can be described as a “paving train” consisting of a paver, a breakdown roller, and a finish roller moving linearly along the road sections to be paved. Trucks haul hot mix asphalt from the plant to the paving site and dump the asphalt into the paver skip. The asphalt is distributed via the spreader on the road surface and the skip becomes available for another batch of asphalt. After spreading the asphalt on pavement a breakdown roller compacts it. A quick check is performed and if the process was done correctly a finish roller will finish that road section. After the check, it might be necessary to repeat the roller breakdown compaction and then finish the section. It was found that 90% of the time, the breakdown compaction was done only once.

The studied process is modeled as a MicroCYCLONE model. A schematic of the model network is illustrated in Figure 1. In the network diagram shown in Figure 1, the asphalt paving operation is considered as a series of work tasks represented as squares in the network. Any work tasks is called “COMBI” or “NORMAL” in MicroCYCLONE modeling. Resources to perform these tasks are represented as circles in the network. These available resources are called “QUEUE” in MicroCYCLONE modeling. The resources used for the case study asphalt paving were as follows: Labor; 1 foreman, 1 paver operator, 1 roller operator, 1 superintendent, 4 truck drivers, and 4 laborers. Materials; Hot mix asphalt from batch plant and aggregate. Equipment; 1 paver, 2 rollers, 4 trucks, and 1 asphalt batch plant. The asphalt paving process was studied and broken down into different operations. These operations were monitored to measure the duration of each. Two sets of durations were used for the computer simulation. First, deterministic durations were used. All operations were monitored for many work cycles. Durations were recorded for all these cycles and the “mean” duration was considered the average deterministic duration and used for simulation. Moreover, normal distribution durations were used where the “mean” represented the average duration for that operation and the “standard deviation” was calculated. All durations are given in Table 1.

TABLE I. PAVING PROCESSES DURATIONS

Work Task	Simulation Model Parameters		
	Model Label	***Standard Deviation***	***Duration (minutes)***
Load asphalt at plant	1	1	1.5
Truck travel to site	3	3	27
Dump asphalt into paver	5	1.5	2
Truck travel to plant	6	3	26
Spread asphalt on Pavement	10	2	6
Compact asphalt 1 with roller	16	2.5	17.5
Compact asphalt 2 with roller	21	1	6
Perform check	19	1	1.5
Decision making	23	1.5	2
Finish section	25	3	7

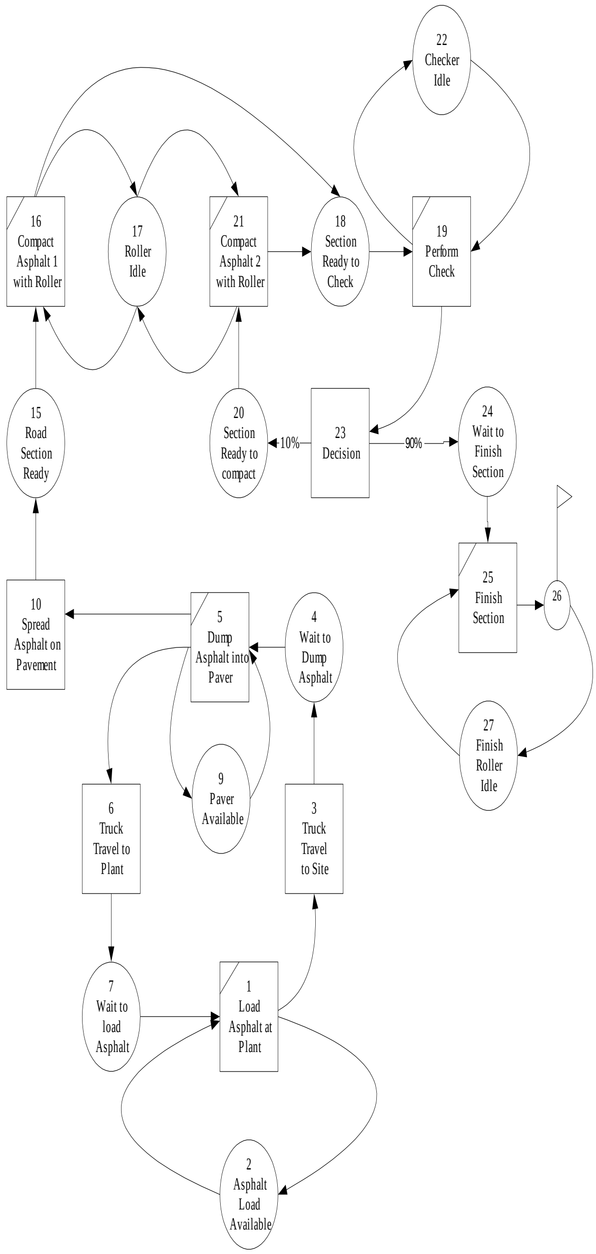

Fig. 1. *Simulation Model*

These work tasks in Fig. 1 are related together by the actual flow of the asphalt paving process on site. The logic of these relationships is shown in Table 2. The simulation model input is illustrated in Figure 2 as a screenshot of the MicroCYCLONE computer software.

TABLE II. TABLE STYLES

Work Task	Simulation Model Logic		
	Model Label	***Preceding***	***Following***
Load asphalt at plant	1	2,7	2,3
Truck travel to site	3	1	4
Dump asphalt into paver	5	4,9	6,9,10
Truck travel to plant	6	5	7
Spread asphalt on Pavement	10	5	15
Compact asphalt 1 with roller	16	15,17	17,18
Compact asphalt 2 with roller	21	17,20	17,18
Perform check	19	18,22	23
Decision making	23	19	20,24
Finish section	25	24,27	26

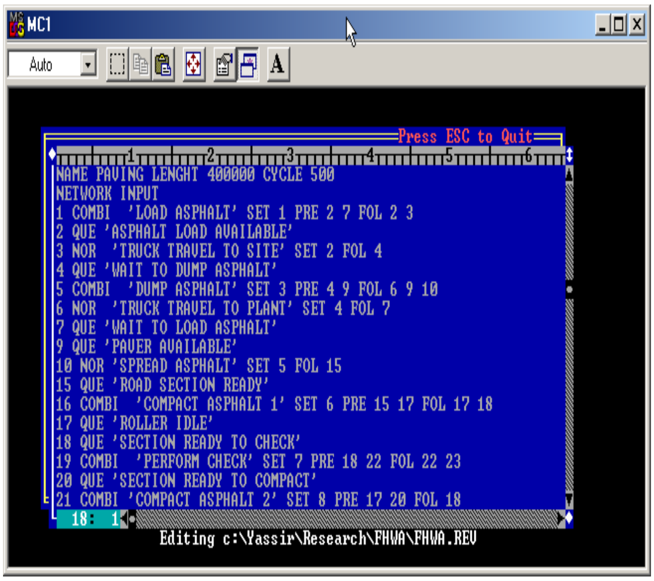

Fig. 2. *Simulation Software Screenshot*

The durations, resources, and network logic are compiled into a computer simulation model and simulated using MicroCYCLONE. The computer simulation for the asphalt paving process was run on for 100, 500, and 1000 cycles. A cycle is defined as completely finishing a truck-load of asphalt. The trucks' capacity in this job was 20 tons. The average production per cycle was 3.1 truck loads/hour for. The process starts with a production rate of about 2.15 truck-loads/hour and gradually increases, as more trucks arrive, to reach the average production rate. This productivity rate is average compared to national productivity rate of 3.0 to 3.7 truck-loads/hour for 20 tons trucks. The computer simulation calculates for each cycle, how the resources are utilized to complete the operation.

Figure 3 shows the model "Queues" utilization which indicates resources utilization. The percentage given is the amount of time that resource was not utilized, i.e. idle. It can be readily noticeable that most resources were either over-utilized or under-utilized. It can be noticed that the paver was idle for about 85% of the cycle time, which means it can be more productive if more trucks arrive and dump asphalt into it. However, the compaction roller was busy for about 99% of the cycle time, which means any increase in production at any other work task can cause a bottleneck delay with the roller. From that analysis we can conclude that an increase in production for a work task does not mean an automatic increase in production for the whole process and may even cause more delays. An optimal resources configuration should be arrived at using sensitivity analysis by changing different parameters simultaneously.

Fig. 3. *Simulation Resource Utilization*

Examining the key work task and queue shown in the simulation model yields a good understanding of the flow of this asphalt paving operation. The key work tasks in the process are:

Asphalt Dumping: includes hauling the asphalt from the plant and dumping it into the paver. Queue 7 “Wait to Load Asphalt” which represents the trucks waiting at the plant to be loaded, has 0.2% occupancy. That means 0.2% of the time there were trucks waiting to be loaded at the plant which indicates trucks virtually did not have to wait to be loaded. The loading process itself represented as Work Task 1 “Load Asphalt” has a mean duration of 1.5 minutes. That means there was an excellent flow of trucks coming in and leaving the plant. However, adding more trucks may increase production while maintaining a good flow at Queue 2.
Compact Asphalt: includes using a compaction roller to compact asphalt after it is spread by the paver. Queue 9 “Paver Available” was occupied 85% of the cycle time. That clearly indicates more trucks can be accommodated. However, as stated earlier, Queue 17 “Roller Idle” was occupied 1% of the cycle time. That means the roller was 99% busy. Since the roller compaction has to immediately follow asphalt spreading by the paver, an increase in the paver productivity will not yield an increase in the overall process productivity without adding more rollers. Queue 27 “Finish Roller Idle” has 63% occupancy, which means it can accommodate more work flow. For the overall process productivity, production is calculated for each cycle and the average is considered the process productivity. The average production per cycle was 3.1 truck-loads per hour. he model simulation was run for 100 cycles as well as for 500 cycles and 1000 cycles. Productivity remained almost the same. For the 100 cycles, productivity was 3.13 truck-loads/hour and for the 500 cycles and 1000 cycles, productivity was 3.07 and 3.06 respectively. There was no significant difference between using deterministic and normal distribution durations.

IV. SIMULATION SENSITIVITY ANALYSIS

The best advantage of computer simulation is the ability to perform sensitivity analysis meaning applying changes to the process and examining results. Sensitivity analysis can be a very powerful and efficient tool since applying changes in real life is costly and time consuming. First, a deterministic set of durations was used for the work tasks. Additionally, the standard deviations were calculated for all work task durations by monitoring and measuring durations for many cycles at the job sites. These mean durations together with the standard deviations were combined to form normal distributions for the durations. Using these normal distributions, the simulation was also run for 100, 500, and 1000 cycles. All resulting productivities are shown in Table 3 as truck-loads/hour.

TABLE III. SIMULATION PRODUCTIVITY

Task Durations	Simulation Productivity Truck-loads/hr		
	100 Cycle	***500 Cycle***	***1000 Cycle***
Deterministic Durations	3.11	3.07	3.06
Normal Distribution Durations	3.12	3.05	3.04

It can be noticed from Table 3, that productivity did not vary considerably by using normal distribution for durations. That means there were not considerable variations and fluctuations in work tasks durations. Moreover, from the simulation analysis, it was apparent the problem areas were the occupancy percentage of the paver and the compaction roller. The paver was occupied 15% of the cycle time. That clearly indicates more trucks can be accommodated. However, the roller was occupied 99% of the time. To increase the occupancy percentage of the paver, additional trucks need to be introduced but that will not increase production unless another roller(s) are introduced since the existing roller has 99% occupancy. A sensitivity Analysis was performed to find the optimal configuration for that specific asphalt paving process. This analysis is illustrated in Table 4 showing productivity in Truck-load/hour for different configurations. From Table 4 it can be concluded that adding more trucks and maintaining one roller will not increase productivity. That was expected because the roller was already busy 99% of the time. However, adding a second roller and increasing the number of trucks will yield gradual increase in productivity. However, an increase of more than 8 trucks will not increase productivity because that will create bottlenecks at the paver and the 2 rollers. Adding an additional roller is very costly. So it can be concluded that a feasible optimal configuration for this process is 8 trucks, 1 paver, and 3 rollers as shown in Table 5. This configuration will yield a productivity of 6.02 truck-loads/hour; almost double the original configuration productivity of 3.12 truck-loads/hour.

TABLE IV. SIMULATION SENSITIVITY RESULTS

Trucks Config.	Paving Roller Configuration		
	1 Roller	***2 Rollers***	***3 Rollers***
4 Trucks	3.12	3.18	*6.02*
5 Trucks	3.12	3.21	*6.02*
6 Trucks	3.12	3.75	*6.02*
7 Trucks	3.12	5.24	*6.02*
8 Trucks	3.12	*6.02*	*6.02*
9 Trucks	3.12	6.02	*6.02*
10 Trucks	3.12	6.02	*6.02*

V. CONCLUSIONS

From the simulation sensitivity analysis, a modified resource configuration was developed. This increase in productivity will yield a reduction in time for the process. It can be safely assumed that adding resources does not mean an automatic increase in cost since the durations are reduced. For example renting 8 trucks for 5 days will cost the same as renting 4 trucks for 10 days. However, the work duration is cut in half. For This study, the original measured productivity for the process is 3.12 truck-load/hour and the modified productivity is 6.02 truck-load/hour. This modified productivity is achieved by increasing the trucks from 4 to 8 and adding an additional roller while maintaining 1 paver and 1 finish roller. If we assume an 8-hours/day shift, the original productivity is 24.96 truck-load/day and the modified productivity is 48.16 truck-load/day. If we assume that the project needed 500 truck-loads to finish that road section, then the project duration with the original productivity will be 20.03 days. The project duration with the modified productivity will be 10.38 days, almost half the original duration. It can be concluded that the project duration can be cut in half without doubling all the resources. Only the trucks and roller were doubled, while the paver and the finish roller were kept the same resulting in total lower cost and shorter duration.

This simulation analysis methodology can be applied to any highway construction process to identify problematic areas and modifying these areas to reduce the process duration. Examining and analyzing a process can result in substantial time reductions. Computer simulation proves to be an excellent tool for such analysis.

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