# Generic Implementation of Lean Concepts in Simulation Models

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Lean production theory, as a production management tool, describes a system that delivers a finished product free from defects, to a customer in zero time, and with nothing left in inventory. Recently, the concepts of lean production have been introduced to construction yet have generally been rejected. Lean construction concepts were recently tested in a simulation environment and were found to be effective. To facilitate the implementation of the concepts of lean production in construction simulation, and subsequently within an actual construction project, a generic approach has been created and is presented in this paper. A special purpose simulation (SPS) template was developed for surface works operations in road construction as an example application. The template provides a means of testing the concepts of lean production on road construction simulation models to quantify their impact on road construction processes. This general approach for implementing lean production theory in construction simulation modeling also proved capable of directing the process of optimizing simulation models.

**Keywords:** lean production theory; optimization; construction simulation; special purpose simulation.

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# 1. Introduction

As a production management tool, lean production theory describes a system that delivers a finished product free from defects to a customer, in zero time, and with nothing left in inventory. Moreover, it can be summarized into three main points: 1) eliminate or reduce all activities that do not add value to the final product, 2) pull material through the process (instant delivery of required materials), and 3) reduce variability by controlling uncertainties within the process.

Lean production was initially developed for the manufacturing industry and has been widely accepted in that field. This concept has only been recently introduced to the construction industry and has not yet been very successful, due largely to the belief that construction has unique and complex projects in highly uncertain environments that are under great time and schedule pressure (Howell 1999), which makes it somehow different from the manufacturing industry.

In addition, the construction industry has historically been very slow to change in many respects, which makes implementing the concepts of lean production theory very difficult. Industry practitioners are wary of implementing new techniques on large, complex projects. Implementing a fundamentally different management system on a multimillion-dollar project could be viewed as risky. For this reason, computer simulation provides an excellent environment to implement the principles of lean production, study their effects, and gain a better understanding of how these principles can be applied to real construction projects. Pioneering work in this area has already been conducted where lean concepts were tested in a structural steel erection model (Al-Sudairi et al. 1999). The results from this implementation were very positive, though the model and approach were process-specific to steel erection.

Thus, the first objective of this paper is to develop a generic approach that will facilitate the implementation of the concepts of lean production theory into construction simulation models. Then, a special purpose simulation template is presented to allow industry practitioners to create computer models of surface works road construction projects that will facilitate both scenario analysis and lean production principles. Finally, a case study of the Anthony Henday Drive Extension project is presented to validate the methodology.

# 2. Background

## 2.1. Construction simulation

Computer simulation is defined by Pristker (1986) as the process of designing a mathematical-logical model of a real world system and experimenting with the model on a computer. Simulation has proved to be a valuable analytical tool in many fields. Particularly, it is powerful when studying resource-driven processes since it provides a fast and economical way to experiment with different alternatives and approaches. Furthermore, key factors in the process can be identified through an in-depth understanding of the interactions of resources and processes.

Construction operations include many processes. The flow between processes and the resource utilization at every step thus determines the performance of the whole project. To understand the interaction of construction processes and the impact of resource supply, the construction project planner can experiment with different combinations of construction processes and varyin g levels of resource supply in a simulation environment to seek the best performance for their construction operation.

Halpin (1973) first introduced simulation to construction with the CYCLONE modeling method. Since then, various construction simulation systems have been created based on CYCLONE, which include INSIGHT (Paulson 1978), RESQUE (Chang 1987), UM-CYCLONE (Ioannou 1989), COOPS (Liu and Ioannou 1992), DISCO (Huang et al. 1994), CIPROS (Tommelein and Odeh 1994), and STROBOSCOPE (Martinez and Ioannou 1994).

According to Hajjar and AbouRizk (1999), simulation modeling is made most effective for use in the construction industry through the specialization and customization of modeling, analysis, and reporting components within the simulation system. This philosophy led to the development of Simphony, a comprehensive platform for both general and SPS application and development.

## 2.2. Lean production theory

Taiici Ohno, an engineer working for Toyota, developed lean production theory as a method of eliminating waste. Ohno shifted the attention of researchers away from the effect of worker productivity on craft production alone towards a consideration of the production system as a whole. Ohno followed the work of Henry Ford in continuing the development of flow-based production management (Howell 1999).

The underlying goal of lean production theory is the avoidance, elimination, or reduction of waste. Howell (1999) defines waste by the performance criteria for a particular production system; failure to meet the unique requirements of a client is considered waste. Howell goes further in outlining this criterion by defining waste as time, space, or material used in the performance of an activity that does not directly contribute value to the finished product. Using these broad definitions for waste, lean production theory attempts to move a production system towards perfection, or zero waste.

Koskela (1992) describes the conventional production philosophy as a “Conversion Model”, which is comprised of the following items:

- A production process is a conversion of an input to an output.
- The conversion process can be divided into sub-processes, which are also conversion processes.
- Minimizing the cost of each sub-process can minimize the cost of the total process.
- The value of the output of a process is associated with the costs (or value) of inputs to that process.

Lean production theory interprets the production system as a series of conversions and flows. Conversion activities are those activities that add value to the final product. Flow activities are those activities that transfer the product to and from conversion activities. A primary goal of lean production theory is to reduce or eliminate the share of flow activities in a project while increasing the efficiency of conversion activities. The following list outlines key principles of lean production theory (Koskela 1992):

- Reduce the share of non value-adding activities.
- Increase output value through a systematic consideration of customer requirements.
- Reduce variability.
- Reduce cycle times.

- Simplify by minimizing the number of steps, parts, or linkages.
- Increase output flexibility.
- Increase process transparency.
- Focus control on the overall process.
- Build continuous improvement into the process.
- Balance flow improvement with conversion improvement.
- Benchmark.

Though lean production theory was developed for manufacturing, the similarities between craft manufacturing and the construction process make lean production theory very applicable to construction.

## 2.3. Simulation modeling and lean construction

Tommelein (1998) indicated that the reason for the development of lean construction principles is that current industry project management tools are unable to describe adequately the construction process at a level on which lean production can be studied. Tommelein (1998) used a game called “The Parade Game” to demonstrate how linked operations affect one another in construction processes. Her developments form the underpinning of the work we describe in this paper.

Al-Sudairi et al. (1999) reported positive results when the following five lean principles were implemented in generic steel erection computer simulation model: precisely specify value by specific product, identify the value stream for each product, make value flow without interruptions, let the customer pull value from the producer, and pursue perfection. An overall improvement was noted; however, the model became volatile and sensitive to variances in the process. It was determined that construction buffers are critical components to the implementation of lean principles. Buffers allow faster processes to continue with a minimum number of stoppages.

This research demonstrated how to incorporate the concepts of lean production into computer simulation models. In addition, the work that has been completed focuses on the application of lean concepts on unique, stand-alone models; a framework for the generic implementation of lean concepts in any computer model has not yet been developed.

# 3. Integrated SPS Template

## 3.1. Surface works operation in road construction

Surface works operations of road construction can be grouped into three main categories: subgrade operations, aggregate operations, and asphalt operations.

### 3.1.1. Subgrade operations

As the name suggests, subgrade operations involve the preparation of subgrade to a specified degree in order to ensure an appropriate foundation for the aggregate and asphalt structures of a road. Depending on the condition of the original ground, there are several different processes that can occur. These processes can involve (but are not limited to) grading the clay to ensure proper elevation, drying or stabilizing the soil and

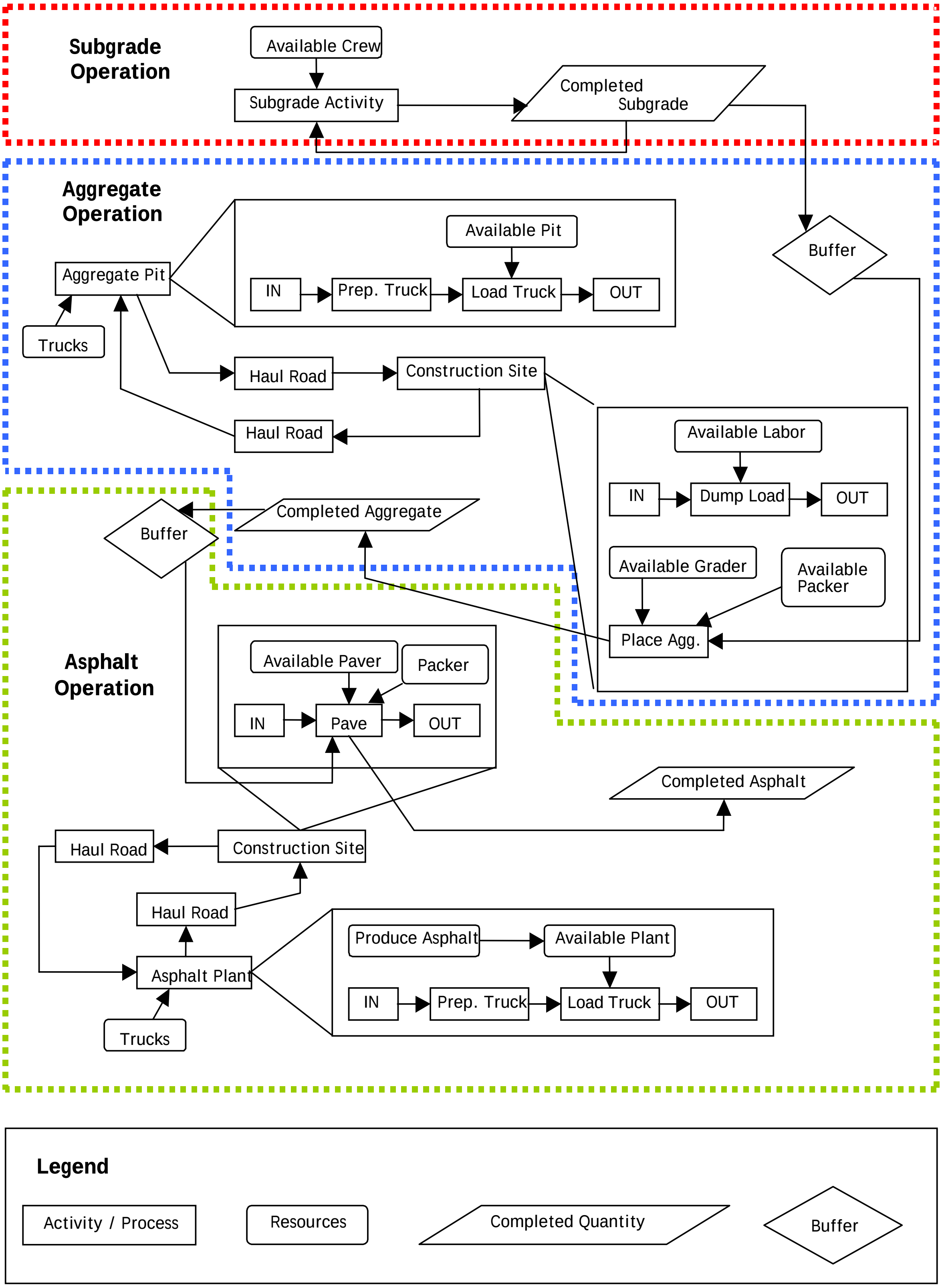

*Fig.1. Surface works road construction operations process flow chart*

re-compacting it to a specified density, or in extreme cases, excavating and replacing unsuitable material from the roadway.

### 3.1.2. Aggregate operations

Aggregate operations involve the supply and placement of aggregate to the construction site. It is desirable for aggregate placement to follow closely behind subgrade preparation in order to “protect” it from poor weather. There are three main sub-processes that combine to govern the overall production rate of the aggregate operation: the aggregate pit, haul cycle, and on-site placement. The resources required for this operation include a loader at the aggregate pit, aggregate haul trucks, site labour, grader(s) to place the material, and packers to ensure that density requirements are met.

### 3.1.3. Asphalt Operations

Asphalt operations involve the production, supply, and placement of asphalt to the construction site. Three main sub-processes govern the overall production rate: the asphalt plant, haul roads, and on-site placement. The resources required for this operation include the asphalt plant, asphalt haul trucks, the asphalt paver(s), and packer(s).

## 3.2. Development of the surface works road construction template

The Surface Works Road Construction (SWRC) template was developed using the flow chart depicted in Figure 1. It shows the main processes of surface works road construction and how they interact. The flow chart was created by simplifying the overall process of road surface construction in which the subgrade, aggregate, and asphalt operations work concurrently.

The simulation begins with the subgrade operation. Once the Subgrade-Aggregate buffer has been reached, the Aggregate operation is allowed to begin. If at any time the aggregate quantity placed overcomes the Subgrade-Aggregate buffer, the Aggregate operation is halted until the buffer is restored. Once the Aggregate-Asphalt buffer has been reached, the Asphalt operation is allowed to begin. The same rules apply to this buffer as to the Subgrade-Aggregate buffer. The model proceeds in this cyclic fashion until the road construction is completed.

As shown in Figure 2, a number of elements are created for SWRC template, including: Construction Site, Subgrade Operation Element, Aggregate Placement Element, Asphalt Placement Element, Asphalt Plant Element, Aggregate Pit Element, Haul Road Element, Aggregate/Asphalt Truck Elements, and Create Truck (Asphalt/Aggregate). The main interface of the SWRC template displays a simplified relationship between the asphalt plant, gravel pit, and road construction site. More precisely, the Construction Site element is composed of a subgrade operation, an aggregate operation, and an asphalt operation as demonstrated in Figure 3. Each of these elements represents the top node in a hierarchy that represents interactions between various resources and activities at its lowest level of detail, as shown in Figure 4. Further information on the SWRC template is available in Farrar (2002).

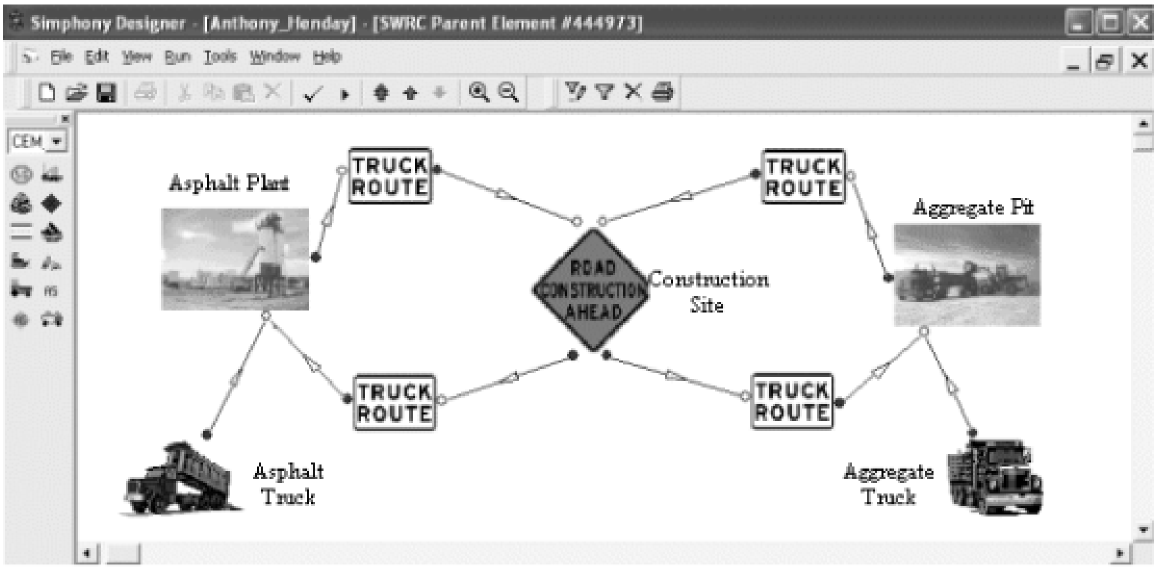

*Fig. 2. SWRC example model*

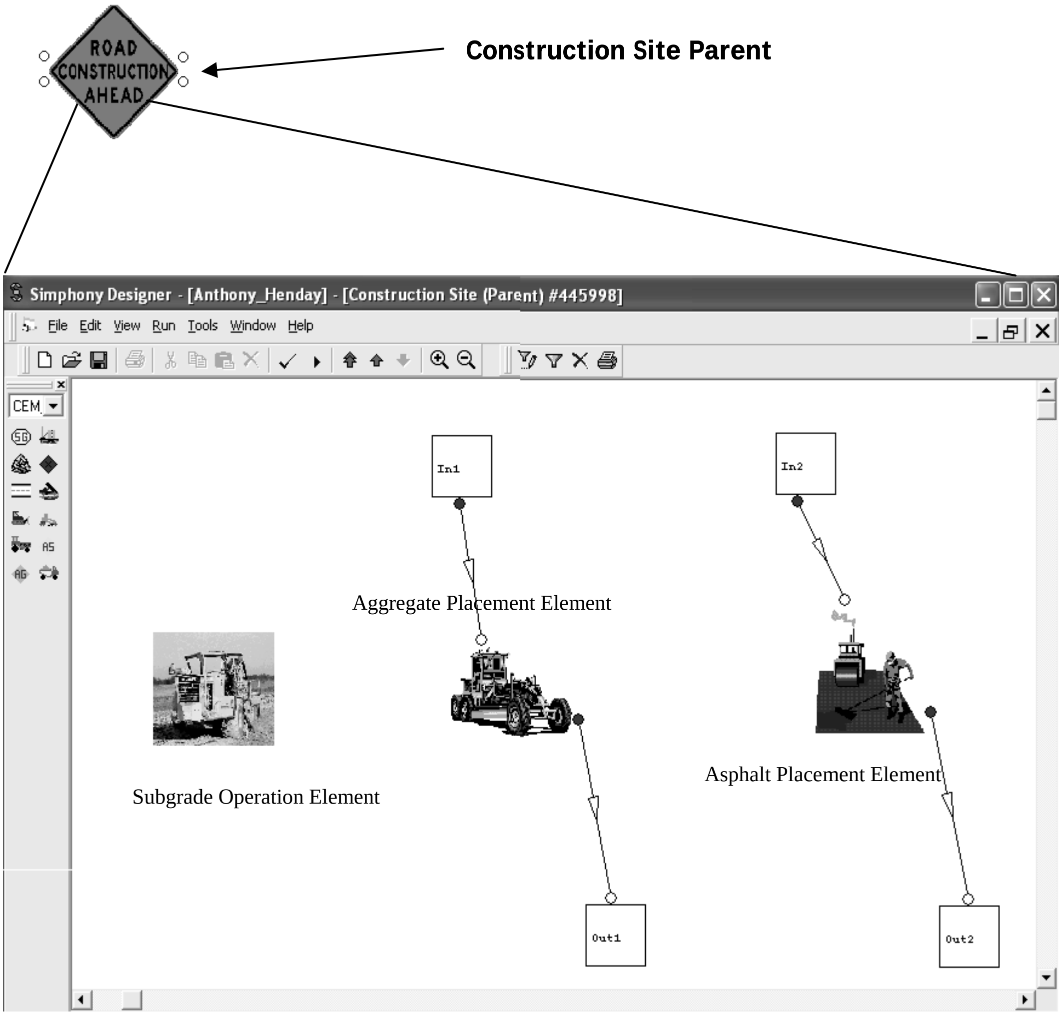

*Fig. 3. Construction site child elements*

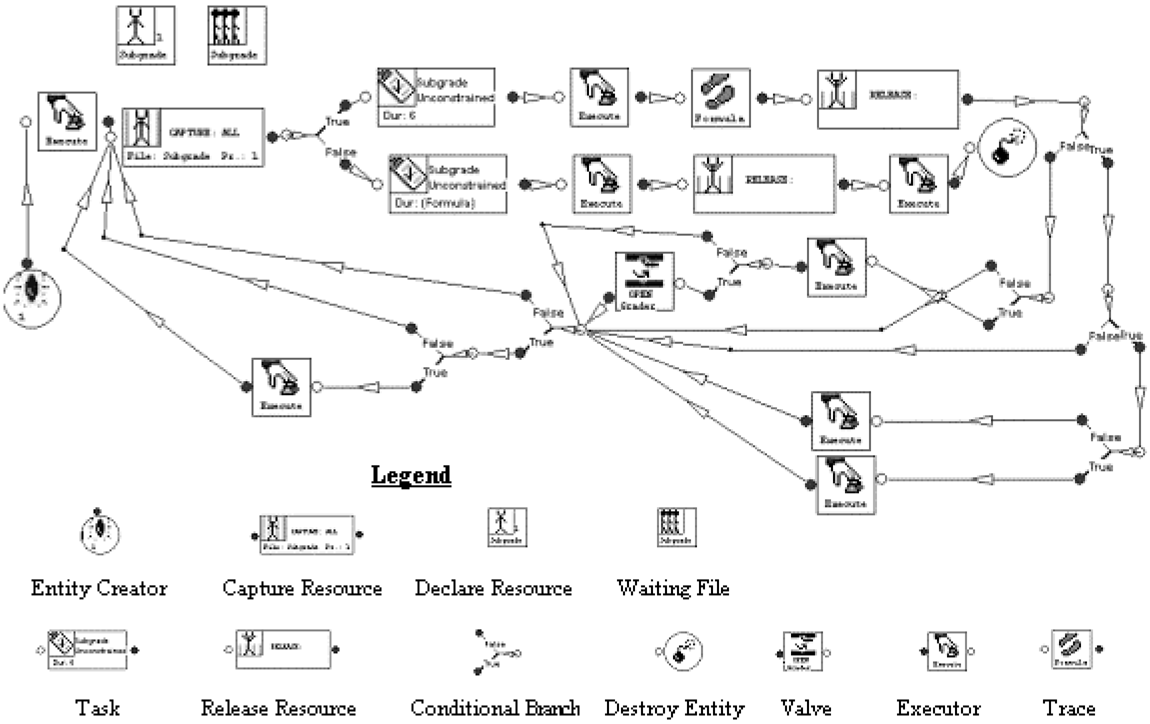

*Fig. 4. Detail of subgrade operation element*

Once a simulation model has been run, the SWRC template produces several statistical outputs, including:

(1) Operational Production Rates. For each operation (Subgrade, Aggregate, or Asphalt) statistical data for hourly production is collected during the course of the simulation. This information is displayed both numerically and graphically.

(2) Resource Utilization. For each resource in the model statistical data is collected for both utilization and queue-waiting times. This information is displayed both numerically and graphically.

(3) Cycle Times. The material haul cycle (aggregate and asphalt) plays a significant role in the overall model. Truck cycle time data is collected during the simulation run and is displayed both numerically and graphically.

(4) Miscellaneous. Other outputs produced by the template include operational durations, overall project duration, measured throughput (overall), and cumulative quantity tracking.

Using these simulation outputs, the user can perform a variety of analytical functions including model sensitivity analysis, scenario analysis, and lean construction theory analysis. Sensitivity analysis allows users to change various input parameters and measure the impact of this change on the model. This enables practitioners to determine which activities are critical and require the most attention. Scenario analysis allows a user to model several different situations, and to compare the output. For example, one could use the model to determine the number of haul trucks to use by modeling several different scenarios and choosing the best result. The model can also be analyzed using lean construction theory.

## 3.3. Application of lean concepts

In this work, lean principles are applied to a simulation model that has been built using a special purpose simulation template instead of a simulation model that stands alone. This difference is very significant because the lean principles that are implemented in this section are done so using a generic set of guidelines that can be applied to any model created using the SWRC template or otherwise.

The principles of lean production as outlined by Koskela (1992) can be separated into three central themes:

(1) Identify and deliver value to the customer: eliminate waste

(2) Increase output value: pull inventory

(3) Create reliable flow: reduce variability

### 3.3.1. Eliminating waste

A construction process is comprised of those activities that add value to the finished project, and those that do not. By definition, a value-adding activity is one that converts the materials to products which are able to meet customer requirements. A non value-adding activity is one that takes time, resources, or space but does not add value (Koskela 1992). Whatever the cause, according to lean principles, if non value-adding activities can be reduced or eliminated, waste in the process can be decreased. Eliminating waste is a fundamental concept of lean production theory.

### 3.3.2. Pulling inventory

The term “pulling inventory” means that material is delivered to the process as soon as it is needed. In most construction projects, material is pushed through each process, forcing the project to slow down or halt altogether until this material has been delivered. As a result, it is the supply of material that pushes or drives the construction process (Tommelein 1998). Pulling material as soon as resources are required is considered instant delivery.

### 3.3.3. Reducing Variability

Variability will exist in any process where operations are dependent on the delivery of material or products or where linked operations have different production rates. One solution that has been developed to respond to variation in construction projects is the use of buffers. According to Howell et al. (1994), buffers can serve at least three functions in relation to shielding work by providing a workable backlog:

- To compensate for differing average rates of supply and use between the two activities,
- To compensate for uncertainty in the actual rates of supply and use, or
- To allow differing work sequences by the supplier and user.

Buffers are important tools because they allow two activities, whose productions are closely linked, to proceed independently of one another (Howell et al. 1994). The SWRC template has two buffers which are used between the subgrade and aggregate operations, and between the aggregate and asphalt operations. They can be used to compensate for the varying production rates of these operations.

### 3.3.4. Guidelines for the implementation of lean principles in simulation models

A number of experiments utilizing the developed SWRC template were performed in an attempt to develop guidelines for the implementation of the lean principles described in Section 3.3.1 into simulation models. These experiments led to the development of the following guidelines, which proved to be the most effective for implementation:

(1) Select all non value-adding activities in the simulation model (candidates for improvement). Use the definition provided by Koskela (1992) in the previous section to focus on those activities that do not add value to the operation.

(2) Set the task durations of the improvement candidates to zero (one at a time). Although, in many cases, eliminating these activities is not possible or practical, doing so will allow one to determine their significance on the model output.

(3) Produce simulation results (run the simulation).

(4) Sort the candidates in order of their significance to the simulation model. This will enable the improvement process to focus on those activities that have the greatest impact on model outputs.

(5) Look for practical activity reduction solutions for the candidates, starting with the activity that has the greatest potential for improvement.

(6) Edit the simulation model to reflect zero-time delivery of required materials. Although this may not be possible or practical, it will allow one to determine the effect that the material delivery process has on model outputs.

(7) Produce simulation results (run the simulation).

(8) Look for practical solutions to improve the material delivery processes (if required). If the material delivery process has a significant impact on model outputs, efforts should be made to make practical improvements.

(9) Look for practical solutions to improve production activities. Only after the lean concepts (value-adding activities, and pull-driven flow) have been introduced to the model should the improvement be focused on production activities.

(10) Introduce buffers to compensate for increased model variability and for differing production rates of linked operations. The lean production improvement process has generally been shown to introduce significant variability into processes. Buffers should be introduced as a final step to compensate for this effect.

# 4. Case Study: Anthony Henday Drive Extension

To implement the concepts of lean production using the proposed guideline, a base model is created using the SWRC template that serves as a benchmark for the experiment. How a specific lean principle influences the SWRC model is determined by comparing the output of a lean concept-improved model with the output of a base model. A base model was created using the SWRC template in accordance with the actual data obtained from the Anthony Henday Drive project. This project is a part of the City of Edmonton’s and the Province of Alberta’s transportation and utility plan and plays an important role in the overall provincial North-South Trade Corridor. The model used in this experiment is of a typical road section, 14-m wide and 1.5-km long. The road structure is made up of 300-mm of aggregate and 100-mm of asphalt on prepared subgrade. The long-distance road and repetitive nature of its construction process made the Anthony Henday Drive Extension an excellent choice for simulation using a model created from the SPS template.

In addition, three base models were used in order to determine how different haul distances affect model outputs when lean principles are introduced; those distances include 5-kms (short), 30-kms (medium), and 100-kms (long), and are used for both the aggregate and asphalt operations.

## 4.1. Validation of SWRC Model

To validate a computer model, two types of data are required. First, input data for the model is required so that the same input parameters are used as were used in the actual project. Second, validation data such as production rates and resource utilization rates were required to compare with the model output. The output produced by a simulation model must yield results relatively similar to the actual project in order for the model to be validated. Both types of data came from a variety of sources, including project time sheets, field quantity reports, trucking haul tickets, time studies, and discussions with industry practitioners.

### 4.1.1. Data for Model Input

Table 1 describes the model input data that was required to accurately model the Anthony Henday Drive Extension Project. Several of the model inputs are in the form of statistical distributions. Uniform (UNI), Triangular (TRI), and Beta (BETA) distributions were used. Uniform and Triangular distributions are often used because their meaning is easily understood and has the smallest data requirement. The Uniform distribution is the simplest continuous distribution in probability. It has a constant probability density on an interval (a, b) and zero probability density elsewhere. The distribution is specified by two parameters: the end points *a* and *b*. Triangular distribution is typically used to describe a subjective analysis of a population based on the knowledge of the minimum and maximum and an average value in between. It is a very useful distribution for modeling processes where the range of variables is known, but data is scarce. A Beta distribution is more complicated. This type of distribution is good for representing data that has been previously collected, because it is considered a flexible distribution. The input values that were determined through detailed analysis and data collection were fitted with Beta distributions.

*Table 1. Anthony Henday Drive validation model input parameters*

| Element | Input Description | Value | Source |
|---|---|---|---|
| Construction Site | Total Road Area | 123,000 $m^2$ | Field Quantity Report |
| Subgrade Operation | Production Rate | UNI(550,700) m2/hr | Industry Practitioners |
| Aggregate Operation | Grader Production Rate | TRI(700,720,780) tonne /hr | Industry Practitioners |
| | Truck Dumping Time | UNI(2,5) min. | Assumption |
| | Aggregate Pull | 1.74 tonne/$m^2$ | Physical Property of Aggregate |
| | Subgrade Buffer | 12,500 $m^2$ | Field Quantity Report & Time Sheets |
| Asphalt Operation | Paver Placement Rate | BETA (1.07,3.58,449.42,1804.80) tonne /hr | Paver Time Study |
| | Truck Positioning Time | TRI (0.50,0.90,2.00) min. | Paver Time Study |

| | | | |
|---|---|---|---|
| | Asphalt Pull | 0.234 tonne/m$^2$ | Physical Property of Asphalt |
| | Number of Pavers | 2 | Industry Practitioners |
| | Aggregate Buffer | 31,000 m$^2$ | Field Quantity Report & Time Sheets |
| Aggregate Pit | Truck Loading Rate | UNI (500.00,600.00) tonne/hr | Industry Practitioners |
| | Truck Prep. Time | UNI (2,3) min. | Industry Practitioners |
| Asphalt Plant | Production Rate | TRI(300.00,325.00,400.00) tonne/hr | Industry Practitioners |
| | Truck Load Time | UNI(2.00,3.00) min. | Industry Practitioners |
| | Storage Capacity | 300 tonne | Physical Property of Asphalt Plant |
| | Truck Prep. Time | UNI (2,3) min. | Industry Practitioners |
| Aggregate Haul Road | Length | 70 km | Industry Practitioners |
| | Ave. Speed Limit | 90 km/hr | Assumption |
| | Expected Delay | UNI (5,10) min. | Assumption |
| Asphalt Haul Road | Length | 24 km | Industry Practitioners |
| | Ave. Speed Limit | 90 km/hr | Assumption |
| | Expected Delay | UNI(5,10) min. | Assumption |
| Aggregate Trucks | Number | 23 | Industry Practitioners |
| | Loaded Speed | 90 km/hr | Assumption |
| | Empty Speed | 100 km/hr | Assumption |
| | Capacity | BETA (2.65,3.84,20.85,42.61) tonne | Truck Haul Tickets |
| Asphalt Trucks | Number | 18 | Industry Practitioners |
| | Loaded Speed | 90 km/hr | Assumption |
| | Empty Speed | 100 km/hr | Assumption |
| | Capacity | BETA (5.45,1.32,11.87,15.77) tonne | Truck Haul Tickets |

## 4.2. Simulation model vs. actual project comparison

Table 2 outlines the model outputs and actual project values that were used for comparison. Production rates were used for this comparison because they are often the most critical numbers for both estimating and job-costing purposes.

*Table 2. Anthony Henday Drive simulation model vs. actual project output*

| Description | Model Output | Actual Output | Difference (%) |
|---|---|---|---|
| Overall Subgrade Production Rate ($m^2$/hr) | 624.7 | 620.7 | 0.64 |
| Overall Aggregate Production Rate (tonne/hr) | 337.9 | 355.1 | 4.8 |
| Overall Asphalt Production Rate (tonne/hr) | 290.8 | 298.5 | 2.6 |
| Paver Utilization Rate (%) | 31.4 | 33.3 | 5.7 |
| Paver Truck Change (%) | 16.4 | 17.0 | 3.5 |
| Project Duration (hrs) | 677.7 | 733.5 | 7.6 |

Through a detailed analysis, the SWRC model was found to perform well insofar as the output of the simulation model and the output of the actual project were extremely close to each other. The reliability of the SWRC template-based model enables both researchers and industry practitioners to perform various lean production theory analyses upon a model that has been proven to resemble closely the actual construction process.

## 4.3. Implementing the “lean” guidelines

Each of the guidelines described earlier was implemented. Their corresponding impacts were quantitatively identified based upon the base model.

### 4.3.1. Identify and deliver value to the customer

A value-adding activity is one that converts the materials to products in order to meet customer needs. Accordingly, all activities of road surface construction were distinguished as either value-adding or non value-adding. Subgrade preparation, aggregate placement, and asphalt placement are value-adding activities because they are the essential steps that convert raw road construction materials into a final product, i.e. road surface. It is assumed that the asphalt plant and aggregate pit are away from the road construction site. Therefore, transportation, as an aspect of conversion encompassed within road surface construction, is defined as value-adding activity. On the other hand, truck preparation and truck position are defined as non value-adding activities because they do not add value to final production and could potentially be reduced or eliminated.

In order to determine the impact that non value-adding activities (improvement candidates) have on the simulation model, they were removed and the simulation was run. For the purpose of this experiment all of the improvement candidates’ durations were set to zero simultaneously in order to determine the model’s “potential for improvement” in this area. The model outputs from this procedure are compared to the base model in Table 4.

*Table 3. Value and non value-adding activities*

| Process | Activity | Value-Adding? |
|---|---|---|
| Subgrade Operations | Subgrade Preparation | YES |
| Aggregate Pit | Truck Preparation Time | NO |
|  | Aggregate Transportation | YES |
| Aggregate Operations | Truck Dumping | NO |
|  | Aggregate Placement | YES |
| Asphalt Plant | Truck Preparation | NO |
|  | Asphalt Production | YES |
|  | Loading of Trucks | NO |
|  | Asphalt Transportation | YES |
| Asphalt Operations | Position Truck | NO |
|  | Asphalt Placement | YES |

In order to determine the impact that non value-adding activities (improvement candidates) have on the simulation model, they were removed and the simulation was run. For the purpose of this experiment all of the improvement candidates' durations were set to zero simultaneously in order to determine the model's "potential for improvement" in this area. The model outputs from this procedure are compared to the base model in Table 4.

Table 4 shows an overall improvement of the model's performance. When the non value-adding activities are removed from the process, however, the improvements change as the haul distances vary. Generally speaking, the percent improvement, as compared to the base model, decreased as the haul distances increased. The reason for this is that as the haul distances increase the material delivery delay time also increases. In other words, as the share of non value-adding activities is reduced, their impact likewise becomes relatively small. Although the statistics collected show great improvement, velocity diagrams of each haul distance case yield interesting results. Figures 5, 6, and 7 display the velocity diagrams for each of the haul distances.

As mentioned, the long haul case did not change as significantly as the medium and short haul cases. In those cases (more so in the short case), significant variability was introduced as non value-adding activities were eliminated. The term, "variability", in this respect, is meant to indicate non-continuous production, and not necessarily erratic production values. The aggregate operation, for example, was stopped due to operational interference with the subgrade process a total of 5 times (in both cases) as opposed to the zero times this occurred in the base model (this will be discussed further in Step 10). The data collected from this experiment indicates that in surface works operations, non value-adding activities have the greatest effect on the process when the haul distances are short.

*Table 4. Value-adding activities model output vs. base model output*

| Description | % Change from Base Model | | |
|---|---|---|---|
| | Short Haul | Med. Haul | Long Haul |
| Project Duration | 0.00% | -8.69% | -5.29% |
| Project Throughput | 1.07% | 9.70% | 5.66% |
| Aggregate Operations | | | |
| Total Working Time | -0.45% | -6.92% | -4.88% |
| Total Time | 0.00% | -6.92% | -4.88% |
| Avg. Production Rate | 0.36% | 7.35% | 5.09% |
| Avg. Grader Utilization | 1.82% | 6.68% | 3.04% |
| Asphalt Operations | | | |
| Total Working Time | -27.06% | -14.49% | -8.09% |
| Total Time | -1.35% | -9.73% | -5.80% |
| Avg. Production Rate | 35.00% | 15.30% | 7.18% |
| Avg. Paver Utilization | 46.90% | 17.12% | 19.80% |

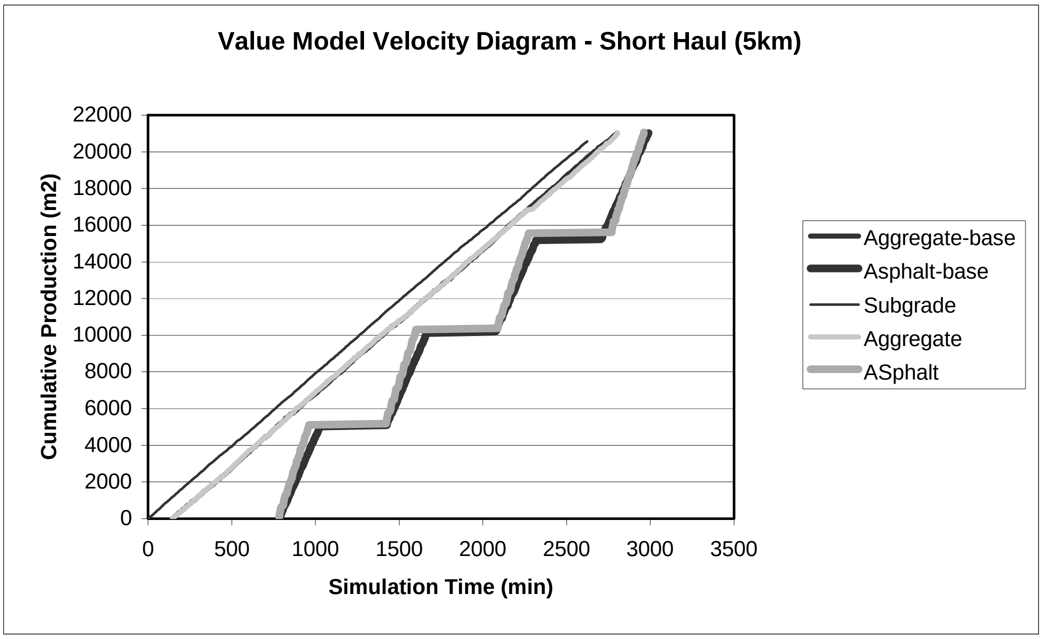

*Fig. 5. Value-adding model vs. base model – velocity diagram (short haul, 5-kms)*

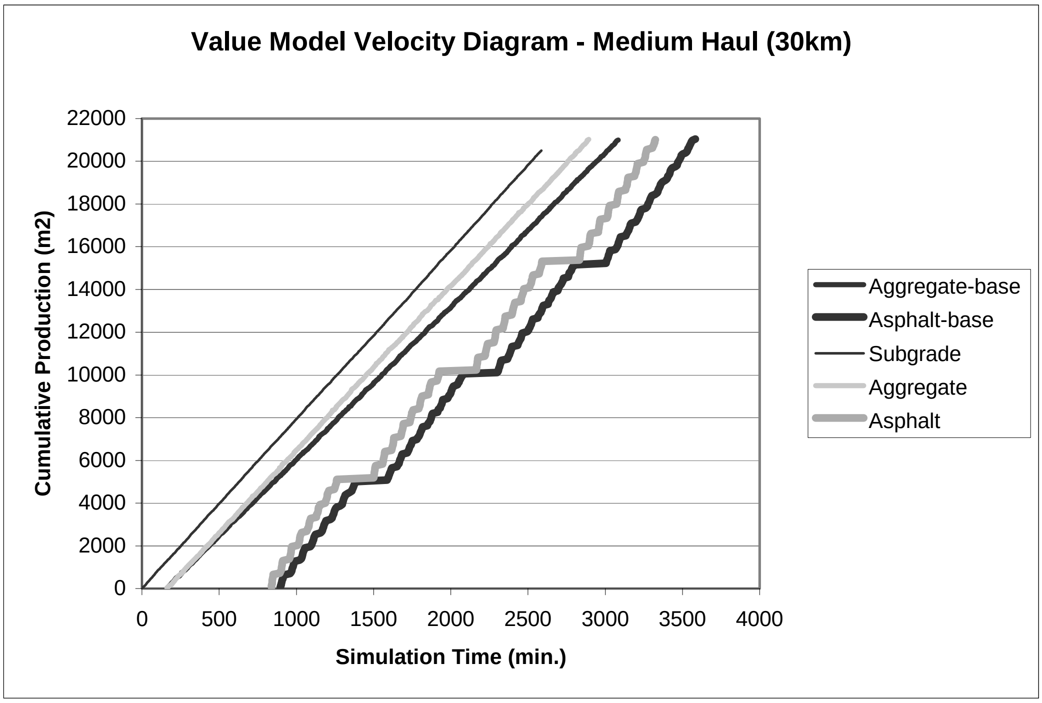

*Fig. 6. Value-adding model vs. base model - velocity diagram (med. haul, 30-kms)*

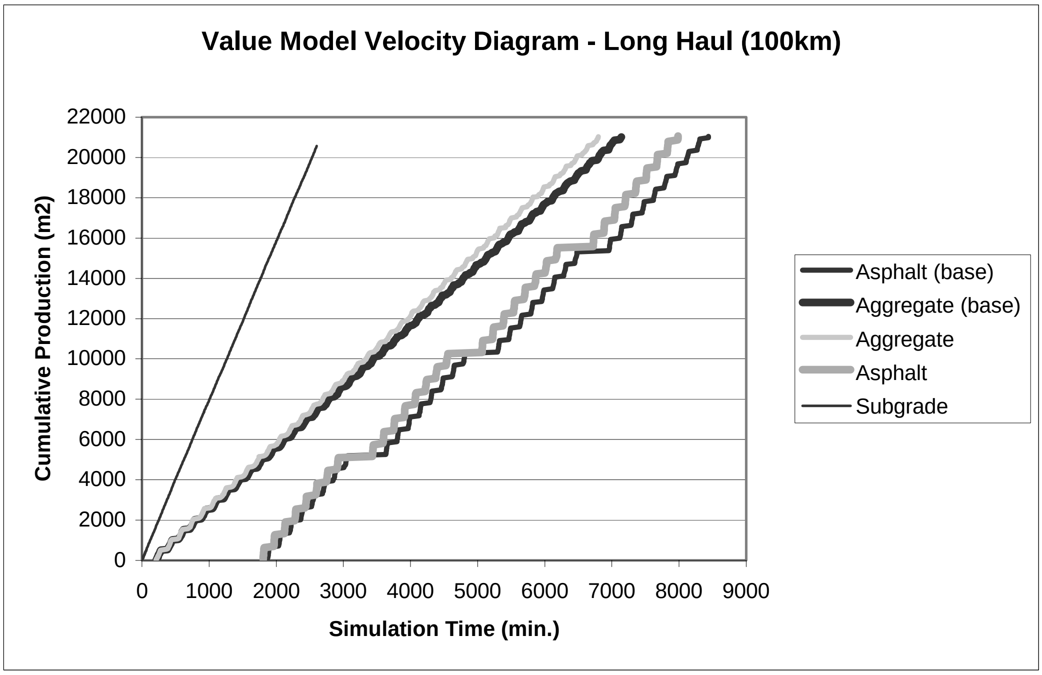

*Fig. 7. Value-adding model vs. base model - velocity diagram (long haul, 100-kms)*

It is clear that non value-adding activities combine to have a significant effect on model outputs; however, it is also desirable to know which non value-adding activities have the most significant effect. This knowledge will enable industry practitioners to have a starting point for determining the activities that should be examined more closely when attempting to improve the system. Using the same experimental procedure as in Step

Three, each non value-adding activity was eliminated, one at a time, so that their individual significance could be ranked. The results of this process are summarized in Table 5.

*Table 5. Ranked non value-adding activities*

| Non-Value-Adding Activity Eliminated | Production Rate (tonne/hr) | % Change | Rank |
|---|---|---|---|
| | **Short Haul (5-kms)** | | |
| | **Aggregate Operations** | | |
| Truck Dumping at Site | 338.1 | 1.05% | 2 |
| Truck Prep. Time at Pit | 338.5 | 1.17% | 1 |
| | **Asphalt Operations** | | |
| Truck Prep. at Plant | 311.0 | 7.24% | 2 |
| Truck Loading at Plant | 336.7 | 16.10% | 1 |
| Truck Position at Site | 307.7 | 6.10% | 3 |
| | **Medium Haul (30-kms)** | | |
| | **Aggregate Operations** | | |
| Truck Dumping at Site | 314.3 | 9.47% | 2 |
| Truck Prep. Time at Pit | 317.7 | 10.66% | 1 |
| | **Asphalt Operations** | | |
| Truck Prep. at Plant | 149.4 | 4.84% | 2 |
| Truck Loading at Plant | 150.0 | 5.26% | 1 |
| Truck Position at Site | 148.4 | 4.14% | 3 |
| | **Long Haul (100-kms)** | | |
| | **Aggregate Operations** | | |
| Truck Dumping at Site | 130.0 | 1.80% | 1 |
| Truck Prep. Time at Pit | 131.9 | 3.29% | 2 |
| | **Asphalt Operations** | | |
| Truck Prep. At Plant | 61.1 | 4.44% | 2 |
| Truck Loading at Plant | 61.2 | 4.62% | 1 |
| Truck Position at Site | 60.0 | 2.56% | 3 |

The data presented in Table 5 suggests several interesting results. For the aggregate operation, the most significant non value-adding activity was "Truck Loading at the Pit" for each of the three haul distances. For the short haul distance, however, the improvement caused by this activity's removal was much more significant than for the other hauls. This is because when the loading activity was eliminated, the short haul resulted in an excess of trucks (enough trucks were hauling to ensure that the Grader was utilized close to 100% of the time). "Truck Dumping at the Site" and "Truck Preparation at the Pit" were shown to have a greater effect on production than the loading of aggregate at the pit. For the asphalt operation, the candidates much more equally shared the improvements. Nonetheless, eliminating truck loading at the plant consistently improved the production rate for all of the haul distances.

It should be noted that the impact of reducing non value-adding activities on a simulation model depends greatly on the complexity of that model. Lee et al. (1999) point out that when activities are simplified for analytical purposes waste in those activities may go unnoticed. The relative simplicity of a computer simulation model compared to actual construction processes, results in certain value-adding activities having, in actuality, non value-adding tasks embedded within them. For example, in an actual construction process the asphalt placement activity might involve inspection, materials testing, survey checks, and/or equipment maintenance, all of which are considered non value-adding. Analyzing activities to this degree using computer simulation becomes impractical because of the highly complex and detailed simulation models that would be required. Such complex models would be less flexible in terms of their applicability and are more difficult to use.

### 4.3.2. Increase Output Value

To determine the impact that the material delivery process will have on the model outputs, the model is changed to reflect a zero-time delivery for both aggregate and asphalt operations. This change can be accomplished by increasing the number of resources transporting the material to the point where the resources that require them are utilized 100% of the time. In the example model this translates into the haul trucks waiting for the aggregate and asphalt operations rather than the other way around. Table 6 illustrates the model output that results from making this change.

*Table 6. Pulling material model output vs. base model*

| **Description** | **% Change from Base Model** | | |
|---|---|---|---|
| | **Short Haul** | **Med. Haul** | **Long Haul** |
| Project Duration | -15.20% | -32.07% | -68.15% |
| Project Throughput | 17.76% | 47.37% | 213.69% |
| Aggregate Operations | | | |
| Total Working Time | -8.30% | -20.71% | -64.07% |
| Total Time | -8.30% | -20.71% | -64.07% |
| Ave. Production Rate | 9.03% | 25.95% | 177.76% |
| Ave. Grader Utilization | 18.73% | 34.09% | 169.91% |
| Asphalt Operations | | | |
| Total Working Time | -59.41% | -79.71% | -91.68% |
| Total Time | -12.94% | -32.71% | -69.76% |
| Avg. Production Rate | 141.86% | 386.18% | 1092.65% |
| Avg. Paver Utilization | 146.05% | 346.40% | 881.29% |

Table 6 shows an overall improvement of the model's performance when the model is changed to reflect zero time delivery. The improvements, however, affect the model in an opposite way to how the non value-adding activities did. Generally speaking, the percent improvement, as compared to the base model, increased as the haul distances increased. The reason for this is that as the haul distances increase, the amount of time required for material delivery increases as well. For large haul distances (if the number of haul trucks is kept the same), the room for improvement is also large. Figures 8, 9, and 10 display the velocity diagrams for each of the three haul distances.

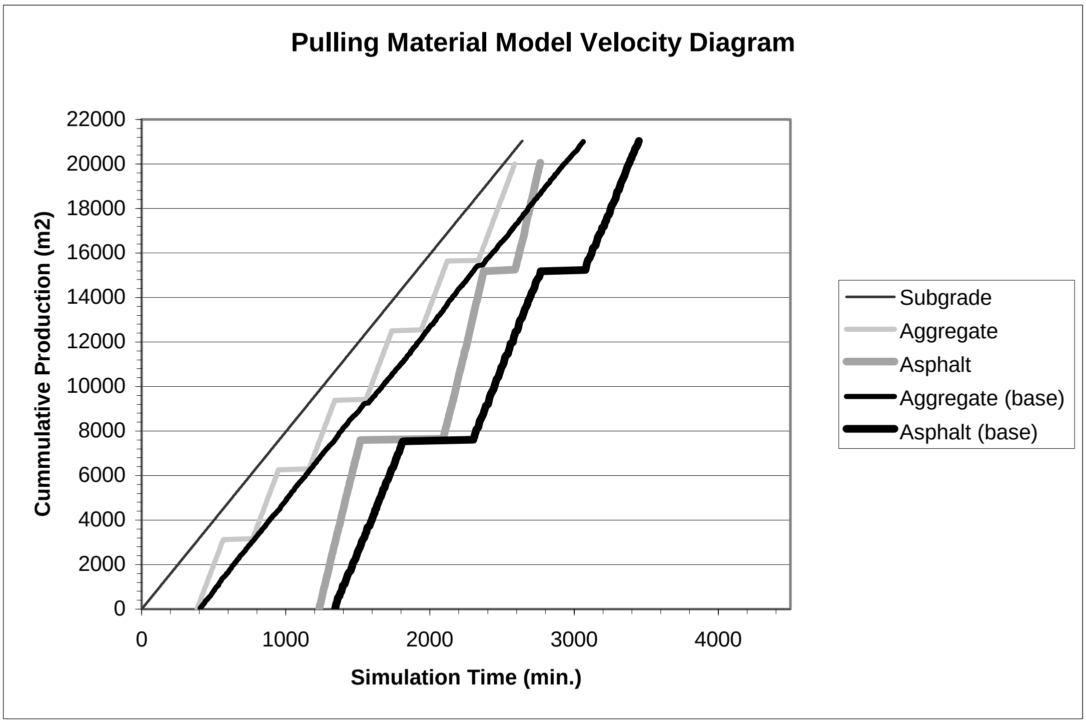

*Fig. 8. Pulling material model vs. base model – velocity diagram (short haul, 5-kms)*

Although the "pulling material" model experienced an opposite effect in terms of the reaction to haul distances, a similar effect was observed in terms of process variability. The aggregate operation, for example, was stopped due to operational interference with the subgrade process a total of 5 times (in both cases) compared with zero times in the base model (just as in the non value-adding experiment). This will be discussed in the next section, however it is clear that introducing the concepts of lean production increase the differences in the operational production rates. The data collected from this experiment indicates that in surface works operations, "pulling" rather than "pushing" material has the greatest effect on the process when the haul distances are long.

This step is the same as Step 5, except it applies to material delivery activities. In many cases it would be impractical to eliminate these activities from the process. It may be possible, however, to improve them by analyzing the process at a more detailed level. This exercise may include choosing better haul routes, selecting haul trucks with larger capacities, or brainstorming with suppliers to develop a new material delivery plan.

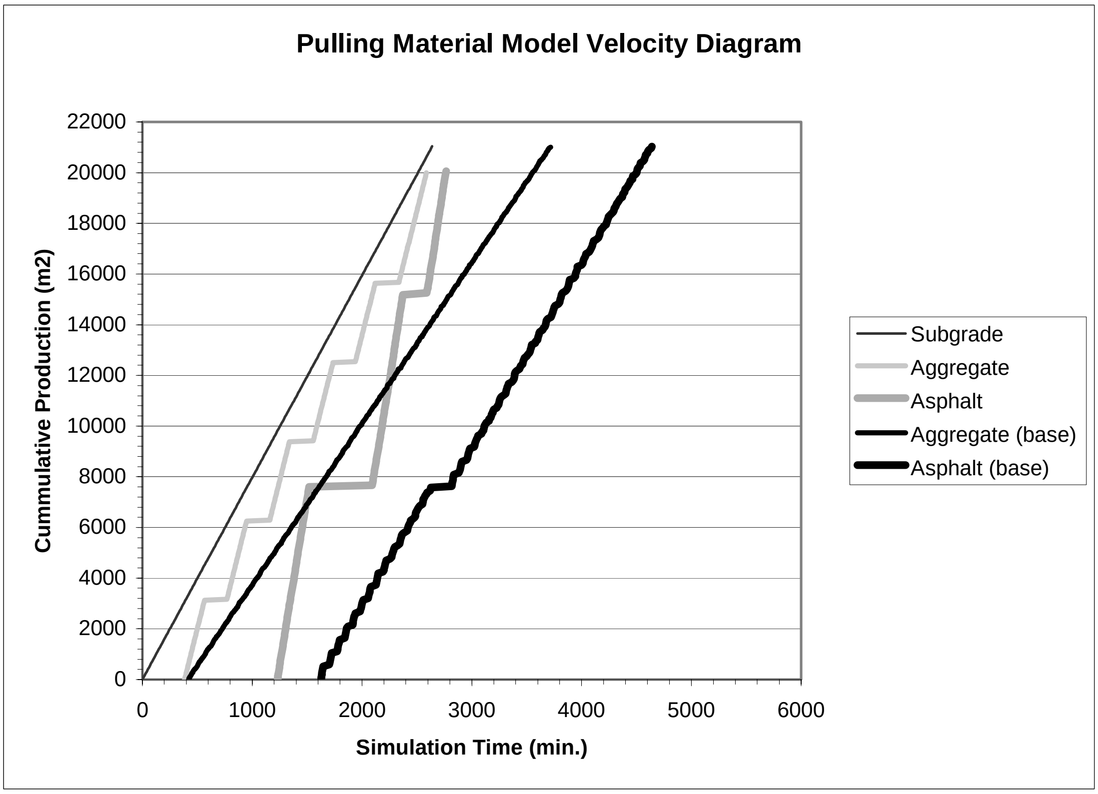

*Fig. 9. Pulling material base model - velocity diagram (med. haul, 30-kms)*

### 4.3.3. Create Reliable Flow

The results of changing the base model to reflect value-adding activities and zero-time delivery showed significant improvements with regard to production rates. However, the velocity diagrams shown in this section, demonstrate that operational buffers are required to control the impact that linked unbalanced operations have on one another. Howell et al. (1993) recommended that “once an operation is underway, isolating sub-cycles by establishing buffers and eliminating shared resources is the first step to performance improvement in uncertain and/or unbalanced situations”. While buffers are certainly necessary in order to achieve a balanced system, they should not be the first step taken towards process improvement. The base model velocity diagram for the medium haul distance (Figure 6) depicts a fairly balanced system. The production lines of each operation are nearly parallel. As lean concepts were introduced, the processes within the model became unbalanced, resulting in operational interference. Therefore, it only makes sense to adjust the operational buffers only after the other lean concepts are introduced into the model; doing otherwise would be counter-productive. Buffer optimization can be done to reduce model variability by running the model several times and experimenting with differing buffer sizes.

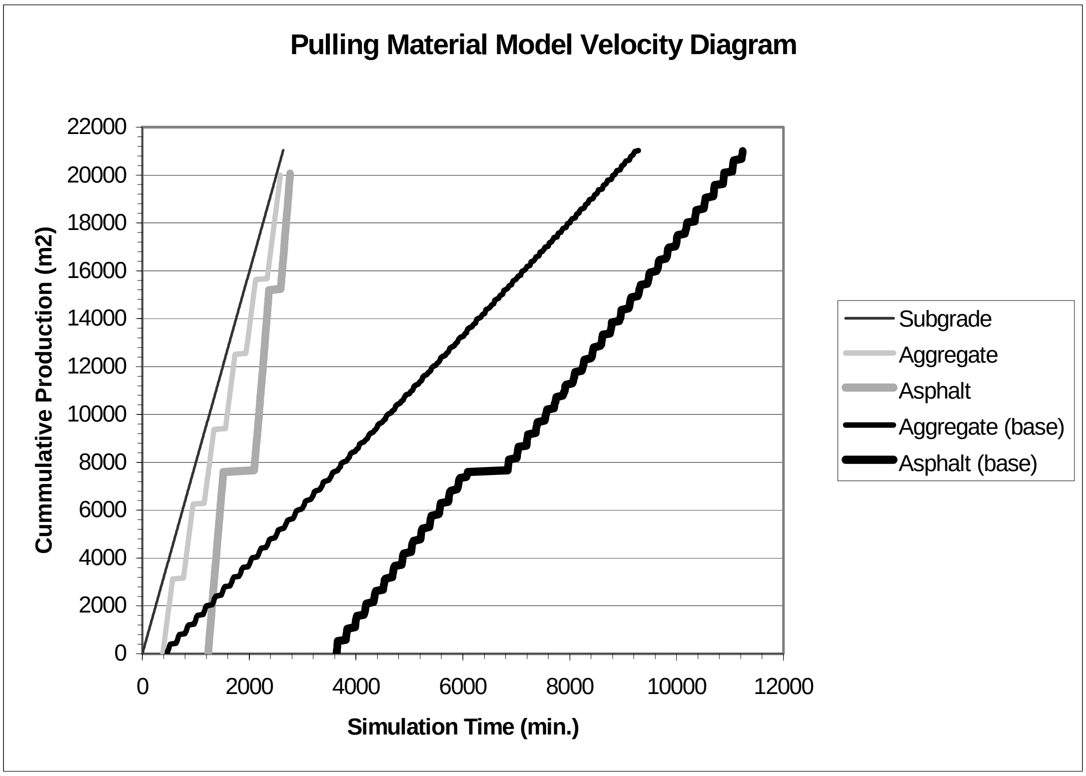

*Fig. 10. Pulling material model vs. base model - velocity diagram (long haul, 100-kms)*

## 5. Conclusion

The research contained in this paper ultimately presents a systematic approach for the application of lean production theory in computer simulation models. This is accomplished through development and experimentation using a special purpose simulation template designed for research in surface works operations of road construction.

The improvements demonstrated through the elimination of non value-adding activities and from the implementation of a methodology of pulling material through the process, were significant. The hourly production rate, resources utilizations, and project duration all improved dramatically, as a result of these implementations.

In terms of experimental findings, the effect of applying lean principles to the process was the most significant discovery. Sensitivity analysis using lean principles has shown that a process can improve significantly by focusing on non value-adding and material delivery activities and optimizing the use of buffers. Current thinking in the construction industry focuses improvement on activities that are directly linked with production; this experiment has shown that there is great improvement potential to be had by focusing on other aspects of the operation as well. This is also likely the case for processes other than road works.

An important feature of this work, which distinguishes it from other lean production / simulation experiments, is that it was accomplished using a SPS template. Other such experiments use stand-alone models to demonstrate lean principles. These models require both knowledge of computer programming and an understanding of computer simulation techniques. The SWRC template is flexible enough to model many road construction projects, without the need for such specialized knowledge

Although the results of this experiment are specific to surface works operations, the generic approach used for implementing lean production principles is general enough that it could be used on any simulation model, regardless of the domain.

# 6. Research Contributions

This research has presented the following contributions:

(1) The development of a systematic approach for the application of lean production theory in computer simulation models.

(2) The development of a special purpose simulation template that can be used to create flexible computer simulation models of surface works operations in road construction.

(3) Significant insight was gained as to how the key concepts of lean production theory can improve the surface works operations of road construction.

Lean production can be summarized into three main points:

(1) eliminate or reduce all activities that do not add value to the final product,

(2) pull material through the process (instant delivery of required materials), and

(3) reduce variability by controlling uncertainties within the process.

Although the concepts of lean production have recently been introduced to the construction industry, only preliminary work has been done to integrate them with the concepts of computer simulation.

This paper presents a framework for implementing the concepts of lean production into computer simulation models. This framework posits the creation of a generic approach that practitioners can use to apply lean principles to any computer model regardless of the domain. This approach is important because it enables users to apply lean principles to simulation models and helps to bring them closer to applying these principles to actual construction projects.

In addition, this thesis describes the development of a special purpose simulation template for surface works operations of road construction (SWRC template). This SPS tool allows practitioners to create flexible models of surface works operations in road construction. Model outputs can be used to perform various analytical functions including model sensitivity analysis, scenario analysis, and lean construction theory analysis. The SWRC template has also been used to establish how lean production theory can be used to improve road construction operations significantly.

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