

EFFECTIVE STRATEGIES FOR SIMULATING ONE-OF-A-KIND CONSTRUCTION PROJECTS

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ABSTRACT

Most construction projects are unique with respect to product features and their delivery process. Consequently, customized techniques for analyzing and designing these projects become inevitable. The authors propose use of Special Purpose Simulation (SPS) modeling techniques for such problems and discuss *Simphony.Net*, a discrete event simulation environment, utilities that support such developments. Past studies successfully implemented using SPS modeling are also discussed. Although SPS modeling approaches can be developed faster and are easier for practitioners to use, they are limited to the domain they model. General Purpose Simulation (GPS) is proposed as one way to overcome this limitation. This paper discusses the systematic steps to developing *Simphony* SPS tools, followed by a demonstration of GPS use in validation of such templates. A case study of a road construction project modeled using *Surface Works Road Construction SPS* is presented and validated using a *Simphony GPS* template, as proof of concept.

1 INTRODUCTION

Construction projects are generally unique in nature and therefore fit the definition of “one-of-a-kind projects.” This is not only as a result of the unique features that exist across projects, but also because of the different construction methods, logical sequences and resources requirements involved in the process of their execution, all dictated by special site conditions and user requirements. Moreover, construction projects are becoming bigger in scope and more complex in nature. Consequently, they offer a great opportunity for detailed analysis and planning prior to their execution in order to guarantee project success. Simulation is one of the suitable non-parametric approaches that can be used for this purpose, especially if the projects are characterized by (1) uncertainty, (2) technical and methodical complexity, (3) repetition and (4) requirement for accuracy and integration when detailed (AbouRizk 2010). In most cases, simulation is primarily used to forecast project duration and costs for purposes of guiding the decision-making process (Ahuja and Nandakumar 1985). Other uses of simulation exist, but all are aligned with the ultimate goal of supporting decision-making processes. Over the years, researchers using simulation-based approaches have demonstrated that discrete event simulation is suitable for modeling problems within the construction domain. A number of simulation systems have been developed based on such analysis. Examples of these simulation toolkits include *Simphony* (AbouRizk and Hajjar 1998), *ABC* (Shi 1999), *STROBOSCOPE* (Martinez and Ioannou 1994), *CYCLONE* (Halpin 1977), *CIPROS* (Odeh et al. 1992), *RESQUE* (Chang and Carr 1987) and *INSIGHT* (Paulson et al. 1987).

The majority of these simulation systems support only general purpose type modeling, with the exception of *Simphony*, which supports both General Purpose Simulation (GPS) and Special Purpose Simulation (SPS). AbouRizk and Hajjar (1998), and Hajjar and AbouRizk (2002) demonstrated this in their

papers by showcasing a number of special purpose templates which had been developed in the Symphony environment for analyzing construction related processes. Examples of SPS templates developed at that time include an earth-moving template (AP2-Earth), an aggregate crushing template (CRUISER), a dewatering template and a PERT template.

It can be asserted that in the area of simulation, researchers have achieved adequate levels of proficiency in developing discrete event simulation models to solve problems in the construction domain. However, there is still a lot to be desired with regard to their choice of simulation modeling strategies to adopt for implementation. Most simulation modelers will use general purpose simulation approaches to address problems they are seeking solutions for, without much thought; and yet, this may not be the most efficient way to deal with that specific problem, especially in the construction domain. Since each of these discrete event simulation modeling approaches has its own limitations and challenges when appropriately used, practices need to be reviewed so that the most relevant and efficient approaches are chosen when implementing simulation-based solutions in order to produce desirable results, as demonstrated in this paper.

2 IMPLEMENTING SPS AND GPS MODELING APPROACHES IN SIMPHONY.NET

2.1 The Architecture of Symphony

Symphony is structured in such a way that it provides all the requirements of a discrete event simulation system such as the interface, random number generators, simulation engine, etc. Besides this, it provides other utilities which may or may not be utilized for simulation. Figure 1 shows a schematic arrangement of the different components that exist within Symphony.

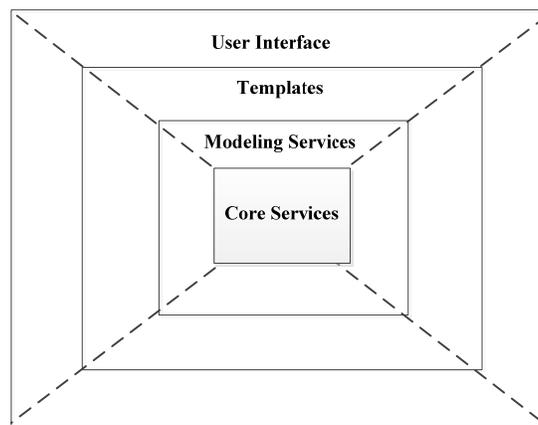


Figure 1: A schematic layout showing the structure of Symphony

The Symphony user interface is comprised of different facilities that support the simulation modeling process. Examples of these include: scenarios, trace facilities and check issues (integrity checks, errors, warnings and messages). The “*Templates*” component includes the general purpose template (*Symphony.General*) and special purpose templates. *Symphony.General* gives access to services which allow creation and manipulation of all general purpose modeling elements and their respective fields such that a modeler can build and execute a simulation model in code without need for the Symphony interface. This component also gives advanced capabilities to modelers using the GPS template in Symphony to perform complex run-time manipulations and interrogations on models developed within the Symphony interface. *Symphony.Modeling* services provide the abstract classes from which the different custom modeling elements can be derived during the development process. These classes have default properties and simulation behaviors, which can be inherited by modeling elements being developed for custom use. It also in-

cludes services for creating and manipulating relationships, and points (input and output points). This Symphony component (*Symphony.Modeling*) is key to the development of SPS templates. At the heart of the Symphony structure are the *Symphony.Simulation* and *Symphony.Mathematics* libraries. These are known to provide core services and other mathematical utilities, respectively. *Symphony.Simulation* provides a number of services such as the simulation engine (i.e. event queue and random number generator), entities (e.g. entity, general entity, batch entity, fuzzy entity and a calendar entity), calendars, resources, waiting files, reports and statistics, which can be used for creating complex simulation behavior within the Symphony environment. The core services and the other utilities can be used within the GPS template as well. *Symphony.Mathematics* is a mathematics library which provides the statistical distributions, matrix classes, optimizer classes and other useful mathematical special functions such as the error function, gamma and beta functions, $\text{get minimum}[x_1, x_2, \dots, x_n]$, $\text{get maximum}[x_1, x_2, \dots, x_n]$, etc.

2.2 General Purpose Simulation Modeling

Nearly all simulation systems provide for GPS modeling capabilities. In Symphony, there are a finite number of modeling elements (28 elements) at a modeler's disposal for GPS modeling. Each of these elements has a pre-defined simulation behavior, input fields, output fields and, at times, statistics. Users are therefore restricted to the functionality and output provided by these modeling constructs. However, there are numerous ways in which these elements can be grouped together to represent logical reasoning in modeling. Effective and meaningful use of elements when constructing models demands creativity and in-depth knowledge of simulation. As a result, building models for operations of medium-to-high complexity requires sufficient simulation expertise, and a lot of time and effort. Decisions regarding the use of GPS approaches need to be strategic to avoid counter-productivity. Examples of ways in which this modeling method is suitable include: (1) as a tool for validating SPS templates that have been developed, (2) as a modeling approach for modeling problems of simple-to-average nature and (3) as an alternative to addressing limitations of SPS tools in modeling unique situations that were never incorporated in the development of the SPS template.

2.3 Special Purpose Simulation Modeling

According to AbouRizk and Hajjar (1998), special purpose simulation is defined as: development of a computer-based environment to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain using constructs that resemble concepts that exist in the real world. The ability for simulation modelers and developers to create their own custom modeling elements does not exist among most current simulation systems. Symphony stands out in this respect because it provides the environment and utilities necessary for the efficient development and implementation of such specialized tools. The development of these tools follows a systematic process demonstrated in the flow chart in Figure 2.

System abstraction, for this type of simulation development, is similar to that done in other general purpose simulation modeling studies and is as important as all the other SPS development steps. The extent to which the system abstraction is done is guided by the (1) objectives of the simulation study, (2) the level of complexity of the system and (3) the capabilities of the simulation system being used. This phase would produce the template specifications, regarding the number of reusable modeling elements (libraries) it will have, their input and output properties and their simulation behavior. This would represent the conceptual design of the template. The next step involves the implementation of the conceptual design to generate a usable deliverable. This is done in a software development environment, usually Visual Studio. Figure 3 shows a sample template at this stage of development.

If the work on each of these modeling elements passes verification and validation requirements, the entire template is deemed ready for modeling use. Verification and validation are a critical aspect of the development because they determine the degree of accuracy of template results and the level of user confidence. For SPS developments, verification and validation is twofold: at the algorithm development and

implementation level and at the modeling level. In such developments, verification is accomplished by (1) using the debug functionality in Visual Studio, (2) using the trace window in Simphony to track the logical sequence and chronology in the processing of events and (3) using counters in Simphony to track the flow of entities into and out of the modeling elements under development. Although other standard verification techniques exist such as visualization, these are not currently supported, and are therefore not proposed for implementation in this approach.

The SPS template can be validated by implementing a case study and comparing the template results with actual field data. Another way to validate is to implement the same case study in another competing simulation tool and compare the results. A good example of this would be the GPS template in Simphony, which has been used for this purpose in a number of past research studies. For validation, standard statistical tests such as the z-score or the t-test can be used to confirm validity of the SPS template. Other tools that can be used include: mat lab – Simulink, and other reliable academic or commercial simulation systems.

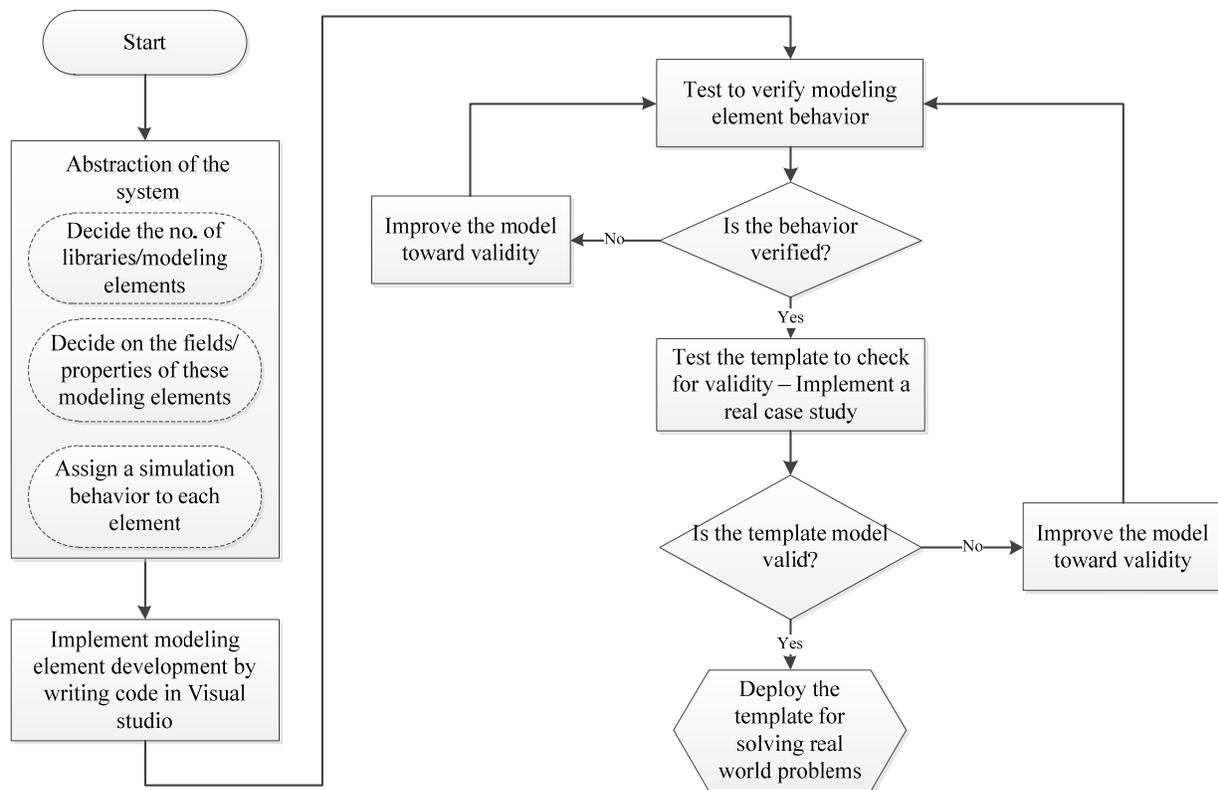


Figure 2: A flow chart illustrating the systematic process of developing SPS templates

Developing simulation modeling systems in this way offers a number of advantages:

- 1) Allows for the development of an independent simulation component in Simphony (a federate) which can seamlessly interact with other components (federates) in a bigger simulation environment (federation) during simulation.
- 2) Building and executing models for a complex system is relatively faster and easier using an SPS compared to using a GPS template.
- 3) SPS provides practitioners with easy-to-use tools for analyzing their operations (Hajjar and AbouRizk 1998).

The authors advocate use of the SPS approach as the most suitable for analyzing unique “one-of-a-kind” projects because it is expected that most of the commonalities that exist amongst such projects will be captured during the abstraction phase and incorporated in subsequent stages of development. This reduces the time and effort required in building models to analyze such projects. Hajjar and AbouRizk (2002) reported that on average, for a graduate student who had attended one basic computer applications course on Visual Basic education and simulation for four, 1-hour lectures and four, 2-hour lab sessions, it took 40 hours to develop a four-element SPS template like CYCLONE. However, it is not uncommon for SPS templates which are limited with respect to modeling an overlooked aspect of the system at the initial stages of the template development (abstraction phase) to be developed. In such a case, it is more feasible and justified to use a GPS template to build a model which includes this aspect than it would be to attempt to redevelop or modify the existing SPS template.

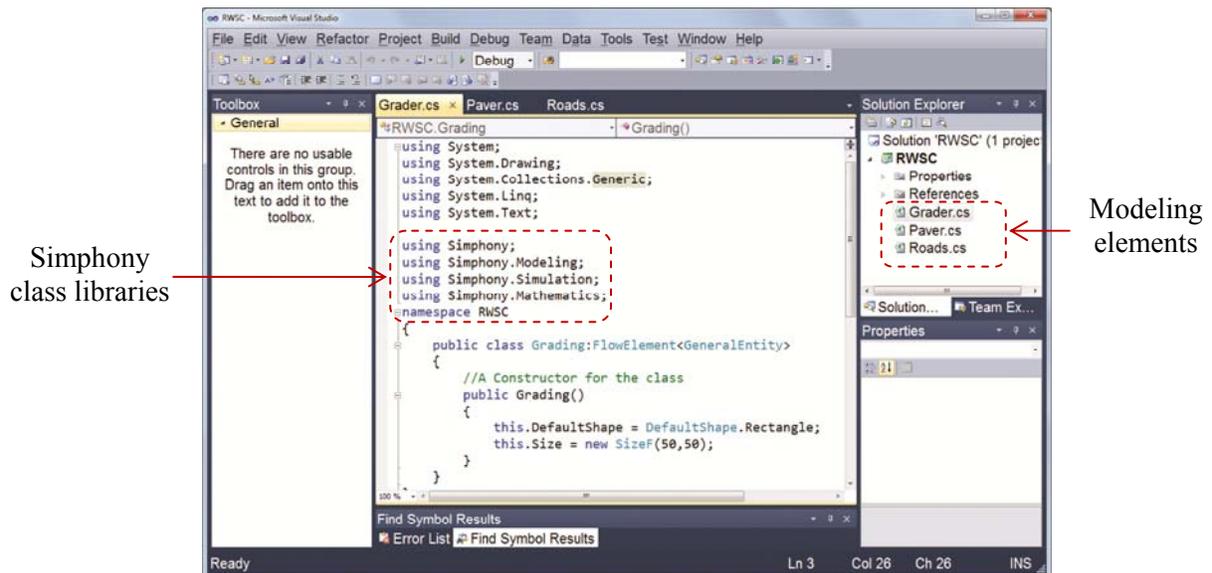


Figure 3: Screen shot of an SPS template under development in Visual Studio environment

The decision to use an SPS approach should be strategic and well thought through in order to guarantee efficiency in the simulation-based approach and accuracy of the results. It is proposed that this approach be adapted for modeling projects in the construction domain, most of which are “one-of-a-kind,” especially when (1) the problem being analyzed is too complex to be accurately modeled using GPS approaches, (2) the model building process is to be simplified, especially if the proposed template is to be used by practitioners in the domain who do not have in-depth knowledge of simulation modeling and (3) the template is to be integrated into larger simulation systems soon after development, or if there is a possibility of integration at some point in the future.

3 A CASE STUDY ON VALIDATION OF AN SPS TEMPLATE WITH SIMPHONY GPS

3.1 Road Construction Project Features and Simulation Models

This section details work that was done on validation of a Surface Works Road Construction (SWRC) SPS simulation template developed by Farrar and AbouRizk (2004), using a GPS modeling approach. Although Farrar and AbouRizk had validated this template using data from the construction site, this study uses a GPS modeling approach to achieve the same, as a means of demonstrating one of the ways in which GPS complements SPS modeling.

The case study (Anthony Henday Drive) used in their validation work is also used here. Anthony Henday Drive is a road located in Edmonton, Alberta, Canada and the section that was under construction included a stretch of road 14 meters wide and 8.79 kilometers long (123,000 square meters of road). A schematic layout indicating some of the road specifications is shown in Figure 4. The road comprised of three components that were to be constructed — the subgrade, the base and the wearing course. Details of inputs used for modeling this case study with respect to activities and resources are summarized in Table 1.

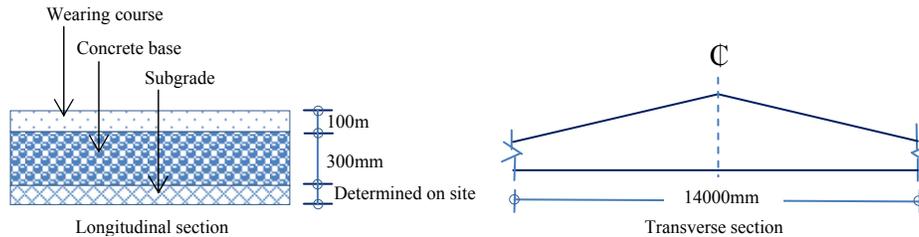


Figure 4: A schematic layout of the Anthony Henday Drive

Table 1: Resource and Production Rate Details for the Anthony Henday Drive.

ACTIVITY DETAILS	PARAMETER VALUE(S)
Scope of work (base case*, other scenarios)	123,000 m ² *; 21,000 m ²
Subgrade preparation production rate (base case*, other scenarios)	Uniform (550,700) m ² /hr*; Triangular (325,500,600) m ² /hr
Aggregate base — grader production rate (base case*, other scenarios)	Triangular (700,720,780) tonne/hr*; Triangular (350,360,390) tonne/hr
Truck dumping time	Uniform (2,5) min
Aggregate pull (base case*, other scenarios)	1.74 ton/m ² *; 0.71 tonne/m ²
Grader	1
Subgrade buffer (base case*, other scenarios)	12,500 m ² *; 1,000 m ²
Asphalt paver placement rate	Beta (1.07,3.58,449.42,1804.80) tonne/hr
Asphalt operation — truck positioning time	Triangular (0.5,0.9,2.0) min
Asphalt pull	0.234 tonne/m ²
Paver	1
Aggregate buffer (base case*, other scenarios)	31,000 m ² *; 5,000 m ²
Aggregate pit — loading rate	Uniform (500,600) tonne/hr
Truck preparation	Uniform (2,3) min
Asphalt plant production rate	Triangular (300,325,400) tonne/hr
Truck loading preparation time	Uniform (2,3) min
Truck loading time at asphalt plant	Uniform (2,3) min
Storage capacity at asphalt plant	300 tonne
Number of asphalt trucks (base case*, other scenarios)	18*; 10
Number of aggregate trucks (base case*, other scenarios)	23*; 12
Truck capacity (asphalt and aggregate)	20 ton
Length of aggregate and asphalt haul (base case scenario*, short haul, medium haul, long haul)	70 km*; 24 km*; 5 km; 30 km; 100 km
Truck speed when loaded	90 km/hr
Truck speed when empty	100 km/hr

3.2 Symphony GPT Model for Road Construction

A hierarchical and modular approach was used for modeling the road construction process. The various operations, namely subgrade, aggregate, asphalt, hauling (of aggregate and asphalt), asphalt plant and aggregate pit were each modeled within a composite element in order to keep the overall model neat, concise and easy to follow. This is illustrated in the layout of the entire model presented in Figure 5.

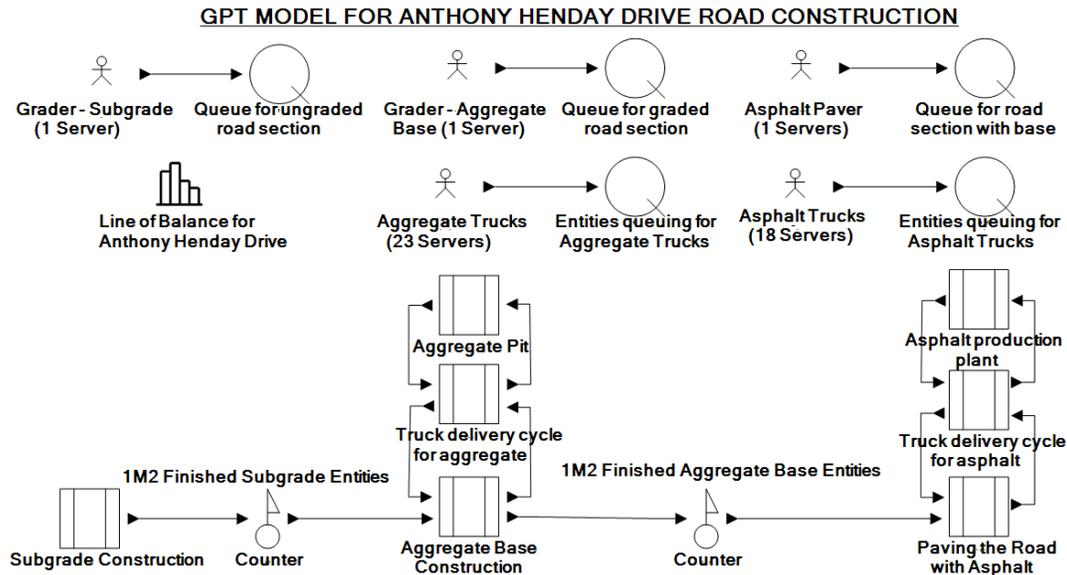


Figure 5: Model layout in Symphony GPT for the road construction process

Entities in the model represented different concepts depending on the module that the entity was flowing within. For example, in the subgrade construction module, the entities represented one square meter of ungraded road and subsequently one square meter of graded road. The resources included the subgrade grader, grader for sub-base construction, asphalt pavers, asphalt plant, asphalt storage, aggregate trucks and asphalt trucks.

3.2.1 Subgrade Construction Module

This phase of the project was modeled as an independent module within a composite element. Figure 6 represents the layout of the model built to achieve this. The create element fires out one entity (which represents the entire road project) at the start of the simulation. This entity flows in a cyclic path through the branch element and the generate element 123,000 times. Every time the project entity arrived at the generate element, one entity representing one square meter of road to be constructed was generated, and the original project sent on a return journey for its next cycle. The project entity cycles through the branch and generate elements until the 123,000 m² of road to be constructed has been created (a test condition coded within the branch element). Thereafter, the project entity is destroyed. One square meter entities arriving at the capture element request for the grader resource, after which they are routed into the “subgrade construction” task element where they are delayed. The task models the duration taken in the actual grading of one square meter of road. After this section has been graded, the entity flows through a counter element and a chart collect element which register the production rate and plot a line of balance production line, respectively.

Before the one square meter entities of finished road are routed out of the subgrade composite element into the aggregate base construction composite element, they are batched so that the subgrade buffer is modeled. This is achieved using a “branch” element, two “batch” elements and an “unbatch” element.

A threshold is the cumulative number of entities (1 m^2) that arrived at the “branch” element, at which entities yet to arrive cannot add up to the required buffer. This threshold was used as a test condition within the “branch” element to route entities which arrive before this threshold is reached out through the “true branch” and those arriving after, out through the “false branch.” One square meter entities arriving at the “Batch 12,500 m^2 ” are held back until the 12,500th entity arrives (i.e. the 12,500 m^2 buffer is achieved).

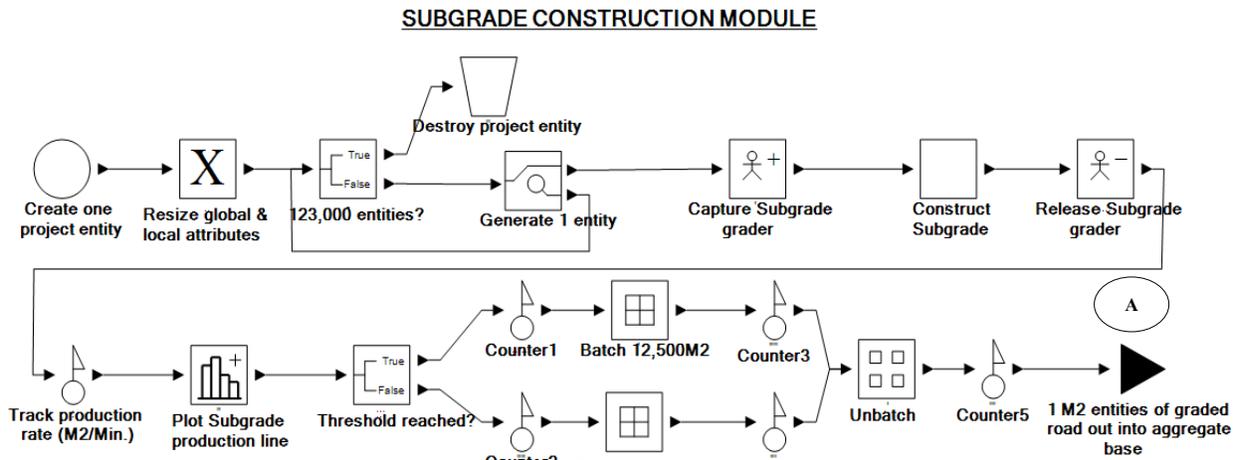


Figure 6: A model for the subgrade construction process

These 12,500 entities are then released as one batched entity which unbatches back into the 12,500 entities when they arrive at the “unbatch” element. The same principle holds for entities routed to the “Batch 10,500 m^2 ” batch element. One square meter entities of graded road are then routed into the “Aggregate Base Construction” composite element through the output port labeled “A*.”

3.2.2 Module for the Construction of the Aggregate Base

Entities arriving at the Input port labeled “A*” of the “Aggregate Base Construction” composite element represent one square meter of finished graded road. These entities are directed towards the branch element labeled “Models aggregate to be delivered by truck.” The first arriving entity samples (from a beta distribution specified in Table 1) the tonnage weight that the truck will deliver. The equivalent tonnage of entities arriving thereafter is added up until the sampled weight to be carried by truck is reached. In the process of accumulating the required tonnage, all arriving entities are routed out through the “true branch” of the branch element and destroyed, with the exception of the entity that achieves the desired tonnage of aggregate to be delivered by the truck. It is regarded as the last entity for this aggregate order cycle. A parameter referred to as “aggregate pull” was used to obtain the equivalent tonnage for each entity (i.e. square meter). The entity that arrives just after the last entity triggers the start of a new aggregate-order-cycle in which the weight to be delivered by the next truck is sampled and the tonnage from arriving entities cumulated until this sampled weight is achieved.

One of the floating point attributes of the last entity is tagged with the sampled weight to be delivered by the truck, and is then routed out through the “false branch” to the capture element where it requests a truck resource. If there is no truck available, the entity is queued, or else it is granted a truck resource and is sent out into the “Truck delivery cycle for aggregate” composite that models its travel to and return from the aggregate pit. Within the “Truck delivery cycle for aggregate” composite element, there are two task elements which delay the entity flowing through for the duration required to travel to the aggregate pit and back to the construction site, respectively. Within the aggregate pit, arriving entities (each representing a truck) request the aggregate quarry, and if granted are delayed for just the time required to be

loaded with the desired tonnage. Otherwise, the aggregate truck entity is queued. Filled trucks return to the site by flowing through the “Truck delivery cycle for aggregate” composite element.

Entities returning from the aggregate pit back to the “Aggregate base construction” composite element are routed through the input port labeled “B*” into a task that models the dumping of the load. Thereafter, the truck resource is released and a grader for the base construction is requested. If a base grader is granted to the entity, it proceeds to an execute element where the aggregate tonnage that the entity represents is converted into equivalent square meter coverage. The entity is tagged with this number of square meters so that this number of entities is generated when the entity arrives at the “generate” element. The generated entities each represent one square meter of road to be constructed and are processed one at a time within the task element labeled “Duration for constructing 1.74 Tonne.” Entities leaving the task element are generated so that the original entity is retained and accumulated until the entire truck load has been constructed, then the base grader is released. A copy of this entity flows through the chart collect element which plots a part of the production line for the aggregate base construction in the line of balance chart. These entities proceed into a branch and batch elements that model the 31,000 m² buffer between the aggregate base and the asphalt construction. After the buffer is achieved, a batched entity is released into the “unbatch” element, which unbatches it back into one square meter entities that get routed into the “Paving the road with Asphalt” composite element.

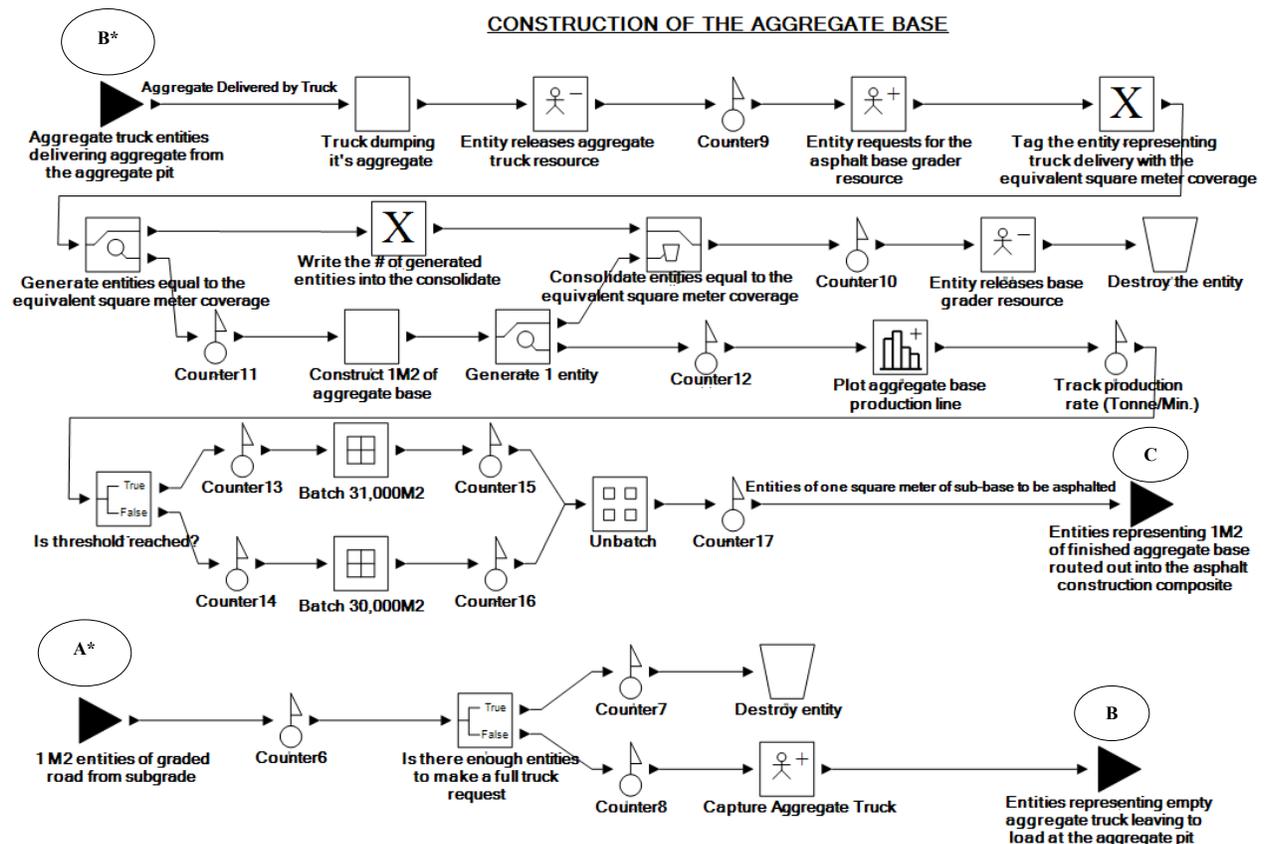


Figure 7: Model for the aggregate base construction process

3.2.3 Module for the Construction of the Asphalt Layer

The logic modeled in the asphalt construction composite element is similar to that described within the composite that models aggregate base construction. Entities, each representing one square meter road section of constructed aggregate base, flow into the element through the input port labeled C*. Entities repre-

senting empty asphalt trucks depart through port D and return full with asphalt at port D*. This asphalt is processed through the elements in a manner similar to the aggregate base construction module, the production is tracked and plotted in a line of balance chart and the entities are then destroyed. Figure 8 represents the model layout of the asphalt construction module.

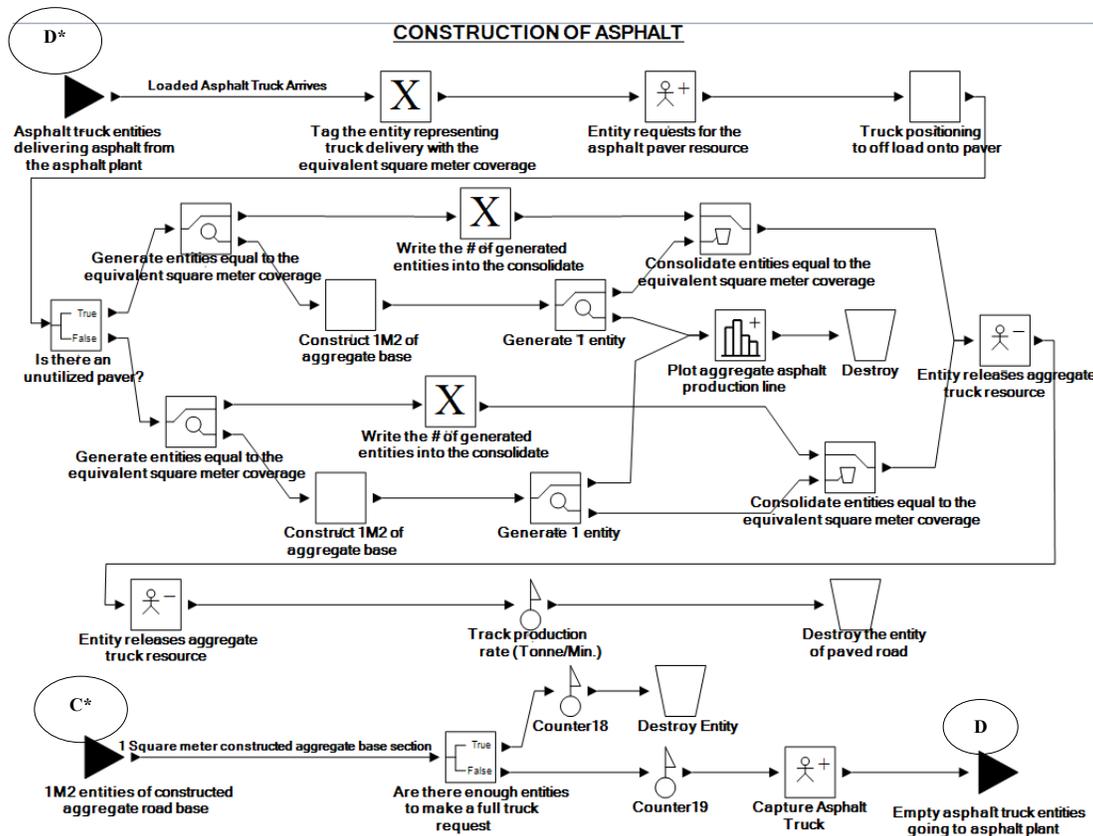


Figure 8: Model for the construction process of the asphalt

3.3 Simulation Model Results

Simulation results for the base case (123,000 m²) were obtained from the Symphony GPS model and compared to those obtained from the project site and the SWRC SPS template. Table 2 summarizes these results and the error margin associated with each estimated parameter.

Table 2: GPS Model Results Compared to Site and SWRC Results.

Parameter	Actual Project Data	SPS-SWRC Results	GPS Results	% Error Margin SPS-SWRC	% Error Margin of GPS
Subgrade production rate (m ² /hr)	620.7	624.7	622.2	0.64	0.24
Aggregate base production rate (tonne/hr)	355.1	337.9	305.5	4.84	13.97
Total project duration (hrs)	733.5	677.7	680.66	7.61	7.20

The error margin in Table 2 for the SWRC and the GPS model seem to follow a similar trend. For the parameters reported in Table 2, the average error for the SWRC SPS template is 4.36% while that for the

GPS model is 7.14%. This shows that results from the GPS and SPS models are comparable hence the GPS template in Symphony can be used for validating SPS templates with confidence.

The GPS model was then modified to replicate the lean construction scenarios experimented with in the SWRC SPS template. Two scenarios were replicated, the short haul (5 kms) and the long haul (100kms) for aggregate and asphalt. Input data summarized in Table 1 was used in the model. Line of balance charts and values generated for the total duration were compared. Figure 9 and 10 shown the generated charts from the SWRC and GPS model in each scenario. For the short haul, the duration for constructing the road was approximately 3,500 minutes for the SWRC and approximately 3,400 minutes in the GPS model, while for the long haul, values of 10,500 minutes and 10,000 minutes were obtained from the SWRC and GPS models, respectively. Results from both approaches are not far from each other, confirming that the SWRC SPS template is valid.

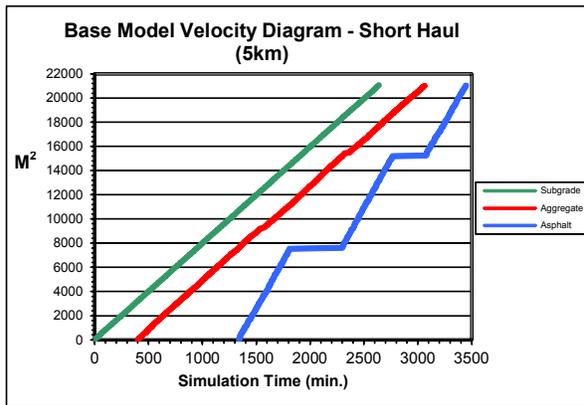


Figure 9a: Line of balance from SWRC template

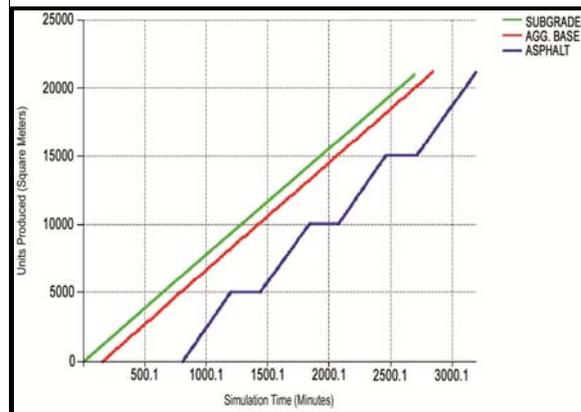


Figure 9b: Line of balance from GPS

Figure 9: Line of balance charts for the short haul scenario (5 kms)

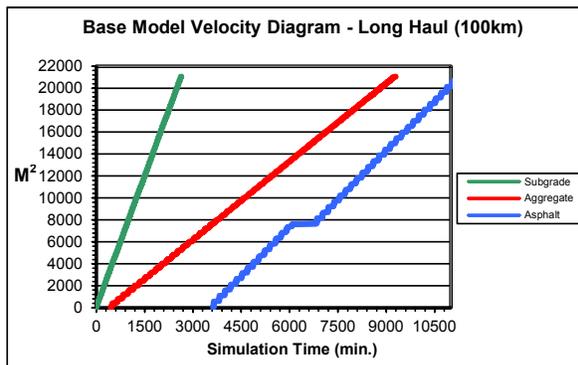


Figure 10a: Line of balance from SWRC template

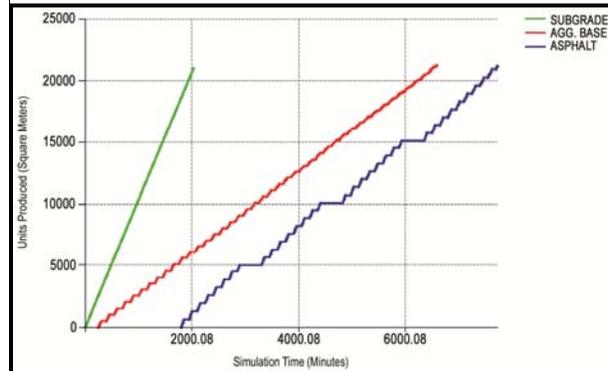


Figure 10b: Line of balance from GPS

Figure 10: Line of balance charts for the long haul scenario (100 kms)

The trend of the production lines shown in Figure 9 and 10 is very similar with respect to the slope and smoothness, with the exception of the asphalt production line which has three steps in both GPS scenarios compared to the scenarios in the SWRC which have two steps in the first scenario and one in the second. Production lines generated using the GPS model are more accurate because they depict the 5000 m² buffer constraint that is imposed on the asphalt construction operation.

4 CONCLUSIONS

A case study of a road project has been presented which had been previously used to validate the SWRC SPS template using data collected from the construction site. This project is used to represent a sample one-of-a-kind project within the construction domain. A GPS model built for the same operation produced results that are close to those collected from the construction site. This demonstrates that the Symphony GPS template can be reliably used for validating SPS templates developed in Symphony.

The enormous amount of time spent developing the GPS model and the resulting complexity of this model reinforce the authors' idea of applying SPS approaches for modeling one-of-a-kind construction projects. Details of how to implement such SPS approaches in Symphony have been presented in a summarized manner. The deficiencies of this approach have also been discussed and GPS modeling was proposed as an approach that can be used to address some of the shortfalls of SPS modeling. It has been shown that GPS modeling can be effective for use as a validation tool for SPS templates.

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