

## **Modeling Construction Operations – An Introduction**

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### **Abstract**

Simulation of operations models is a tool that can be used to determine the processes, crew-make-up, equipment, and manpower necessary to complete a task. By using an operations model of the actual procedure, it is possible to evaluate multiple resource configurations and operational designs, and select the one best suited for the overall project. This article will offer a brief background on simulation and its uses in the construction industry, and introduce SDESA (Simplified Discrete Event Simulation Approach) as an option for modelers to use. The model building process will be outlined and then Simulation of Operations will be introduced via a simple pipe-laying model using SDESA. Variations of the basic pipe-laying model reflecting different configurations will be presented, and the pros and cons of each model will be discussed. The paper will then discuss how this simple model was applied to an actual project. Three other applications of simulation to actual projects will be discussed, and how simulation provided decision-making support for these projects.

### **Key Words**

Simulation, simulation of operations, operations modeling, planning, resource, task, resource utilization, scheduling, decision-making, SDESA.

### **Who should read this article**

Planners, Schedulers, Estimators, Construction Managers, Claims Analysts.

# Introduction

## A Background on Simulation

This article will introduce the concept of “modeling of operations” in construction, and what its benefits are when applied to a set of operations. An operations model (modeling) is created to simulate the operation of a real system. An operational model establishes physically correct quantitative relationships among the parts of a real system, and represents real life operations, activities, resources, equipment, labor, materials, rules, and procedures, so as to gain knowledge and information about the system being modeled, leading to an understanding of a certain configuration that best meets the financial and performance goals of a project. Some systems are so complex that they can only be studied in depth by simulating operational models.

A model may be implemented manually or in a software simulation system. Once the model is defined and is ready to be processed, the model may be simulated. Simulation (running) of the model yields statistics that closely mimic the real system. When a model simulates an existing system to a close degree, then the model is “validated,” and may then be used to carry out experiments by varying the model’s configuration (number of resources, durations and flows). It is easier and less expensive to carry out experimentation in the operations model than on the real system.

Simulation of operations has been used to model processes from several industries, including construction, manufacturing, shipping, railroad, medical centers, materials handling, airport operations, etc. The types of simulation models presented here are known as “discrete event” or “next-event models,” as these models are event-driven. The occurrence or the completion of an event triggers other events, which may be processed if resources are available or are placed in a queue to be processed [1][2].

Simulation of operations models were developed in the late 1950s, with computerized simulation systems such as GPSS (General Purpose Simulation System) and GASP (General Activity Simulation Program) being developed in the early 1960s [3].

The person providing the impetus behind the simulation movement in academia, government and industry was Alan Pritsker [4], but in construction, D. W. Halpin has provided much of the leadership in advancing and teaching the approach. In 1973, he developed a construction-specific simulation system, CYCLONE (CYCLic Operations Network), one of the first systems to model operations using networks of tasks and resources, which greatly simplified modeling [5].

While early simulation systems consisted of specialized procedural languages, the current trend is to represent models as task networks, and to provide graphical-user-interfaces (GUIs) with icons for tasks, resources and paths at the front-end, which is often also the model’s physical space representation of the process (a factory layout or job site). These commercially available modeling systems provide GUIs: ProModel, Siman/Arena, AutoMod, Micro Saint, Simul8 and Flexsim, among others [6].

## Simulation in the Construction Industry

Even though academic simulation tools have been available to the construction industry since the 1960s, its use as a decision-making support methodology for actual construction project has not been notable. This is particularly troubling since a European construction company reports productivity improvements from 30% to 200% as a result of using simulation tools [7]. This paper will present to construction professionals the value of simulation, and possibly steer some into adopting this tool so that other companies may experience similar benefits.

## Modeling Construction Operations

Construction operations are by nature repetitive. Laying brick, erecting steel and pouring concrete are all repetitive. Multi-story buildings and multi-unit housing projects also involve repetitive work processes. Therefore, any analysis of construction operations will involve mostly repetitive operations. Some construction operations may be considered repetitive not because a task is repeated over and over again, but because a series of operations share the same resource, such as a crane.

Estimates and schedules include these repetitive activities, with estimators, planners, and schedulers calculating averages, such as the “average throughput,” in order to determine production rates, estimate costs or installation times. In some cases, due to variability in arrival times, cycle times, installation times and waiting times, the calculated averages are higher than what would be observed in the real system, thus affecting the quality of estimates and financial forecasts.

Operations modeling and simulation can provide insight into the many factors that affect productivity. This may lead the construction team to devise guidelines to manage the variability, and improve efficiency and profitability. For these reasons, simulation is a tool that construction companies should consider using.

## Basic Modeling Constructs

A repetitive construction process, such as “three concrete pours” may be modeled using Activity Networks (such as CPMs) as a sequence of three pour activities: “pour 1, pour 2, pour 3.” It could also be modeled as a task-resource diagram or Activity Cycle Diagrams (ACD notation). An ACD would represent this process as one task and the needed resource(s), such as a crane, shown in a “cycle” to and from the task. A third approach, called the “simplified” activity diagram (AD) notation, depicts this process as a task and the needed resource(s) listed on top of the activity box. Please see Figure 1.

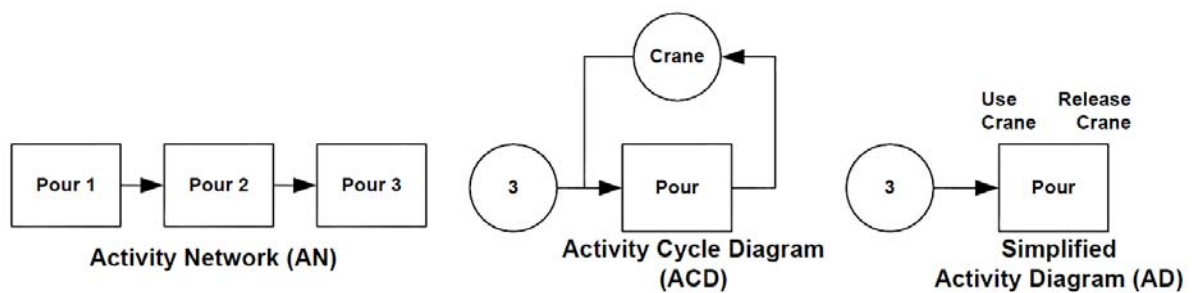


Figure 1 – Different Activity Representations

## Operations Modeling Methodology

Construction operations at the task level (e.g., lift, clean, hook, release, set, pick-up, lay-down, pour, finish, weld, etc.) should be modeled using ACD or AD notation and computerized systems that support these notations, operations modeling and simulation. Five reasons for this preference are offered below:

1. Operations models generally express duration in minutes. Representing these activities in a CPM would require a lot of effort, since each task has to be explicitly defined in an activity network, the number of activities would become very large. Since typical uses of CPMs involve tasks with durations expressed in days or longer, using a CPM to simulate detailed construction processes with resources that cycle in and out to perform related tasks presents difficulties. A CPM would typically have an activity such as “pour slab,” representing not just one pour, but *all* of the pours done in that one day. When a model summarizes a series of tasks into one summary task, it cannot track, analyze or manage the individual resources that execute those detailed tasks.
2. Operations models represent the interaction among the diverse sets of equipment and manpower that are deployed in order to install materials, or move materials or equipment. For example, a crane operations model may account for these uses: erect forms, strip forms, clean forms, handle materials and equipment, and pours. In addition, in a model, the crane process may account for breakdowns, crew breaks, scheduled maintenance and moves to another location. The model would also account for manpower to hook, set, and release the forms, and to manage the lifting and setting process. Resources are modeled to reflect real-world interactions among resources. In the model, during simulation, each “use” and “release” of a resource would *generate* an activity. In a CPM (AN notation) activities explicitly representing resource use and interaction would be difficult to represent.
3. Operations models facilitate experimentation. Changing the number of trucks from 1 to 2 would generate a whole new set of results. In a simulation system, only one variable would have to be changed, thus these systems lend themselves to experimentation once the base model is built. To do this in a CPM would require the revision of many constraints.
4. Operations models maintain statistics relevant to efficiency, waiting times and duration of the process, and they facilitate the management of queues, resource utilization and other statistics. A typical CPM cannot describe in detail what is happening to resources (e.g., percent of time busy, percent of time idle, percent of time waiting on other resources).
5. Operations models introduce random events and probabilities into a model in order to represent the real system properly, such as random or scheduled arrivals (e.g., concrete trucks, precast elements), probabilistic logic (e.g., probability of taking a path is 40%) and probabilistic durations. A typical CPM system does not have this ability.

It is thus recommended that if there is a need to model construction operations, that task-resource models be created and simulated, using a simulation system that supports the modeling of operations.

Conversely, in most cases, simulation models should not be used to represent or analyze processes that are not repetitive or that do not need to be analyzed in detail.

## Steps to Follow in Modeling Construction Operations

Once a decision is made to model and simulate, the study must be kept in perspective. The analyst must consider: project goals, systems, subsystems and how this model fits in the overall strategy of the Project Management Plan. A possible project hierarchy to consider during the pre-simulation phase would be:

- a. Project – This is what is scheduled or planned
- b. System (e.g., structure, excavation) – These are sections in the schedule
- c. Processes (e.g., install steel beams, lay pipe) – A schedule would include activities such as “steel 2<sup>nd</sup> level”, or “lay pipe Area 1.” A process model would include the tasks and resources necessary to erect the steel structure or lay pipe for the project.
- d. Tasks (e.g., lifting beams, set beams, welding, inspect) – These are the tasks in the model. Most CPMs would not include this level of detail.

Some operations that may be modeled are:

- Laying Pipe
- Installing duct banks
- Earthmoving operations
- Tunneling
- Roadwork
- Concrete operations in a high-rise, tunnel, missile igloos, stadiums
- Steel erection in a high-rise, stadiums
- Large site trash management
- On-site fabrication and installation
- Supply chain, off-site fabrication, transportation to site, installation

Some reasons to model may be:

- Estimating durations for certain processes
- Evaluation of equipment configurations, location, quantity and capacity
- Studying efficiency, capacity and waiting times for certain equipment, such as cranes
- Determining physical site constraints on an operation
- Choosing the best travel routes for equipment
- Developing rules or procedures (if ... then do...)
- Determining a Lowest Cost Configuration
- Study of actual site conditions or events on planned productivity

In general, the steps to follow during a simulation study are listed below:

1. Statement of the Problem
  - Why is an operations model needed?
  - What is the problem?
  - What questions will the study answer?
2. Preliminary Cost and Benefit Analysis
  - What is the expected cost of the study?
  - Evaluate costs and benefits of the study.

- Decide whether to undertake the study or not.
- 3. Select modeling platform, processes to be modeled. Draw boundaries; what will be modeled and what will not?
- 4. Define the study methodology. Who will do what? How will the data be collected? How long with the different study tasks take? If necessary, refine the budget estimate for the study.
- 5. List reports, graphics and statistics needed from the simulation in order to support decision-making.
- 6. List model parameters that need to be gathered or defined. Collect durations, flow charts, shifts, arrival patterns and other model details.
- 7. Model creation.
- 8. Simulation and debugging of model (or verification).
- 9. Validate model against real system (as observed). Model statistics should be similar to those observed in the real system.
- 10. Experimenting with model parameters.
- 11. Documentation and Reporting.

## **SDESA (Simplified Discrete Event Simulation Approach)**

### **Selecting SDESA for Modeling Construction Operations**

SDESA is a construction-oriented modeling system designed for relative ease of use. This makes SDESA an ideal modeling platform for students and professionals that want to learn more about simulating construction operations. It was developed by Lu [8]. This system uses Simplified Activity Diagrams (AD).

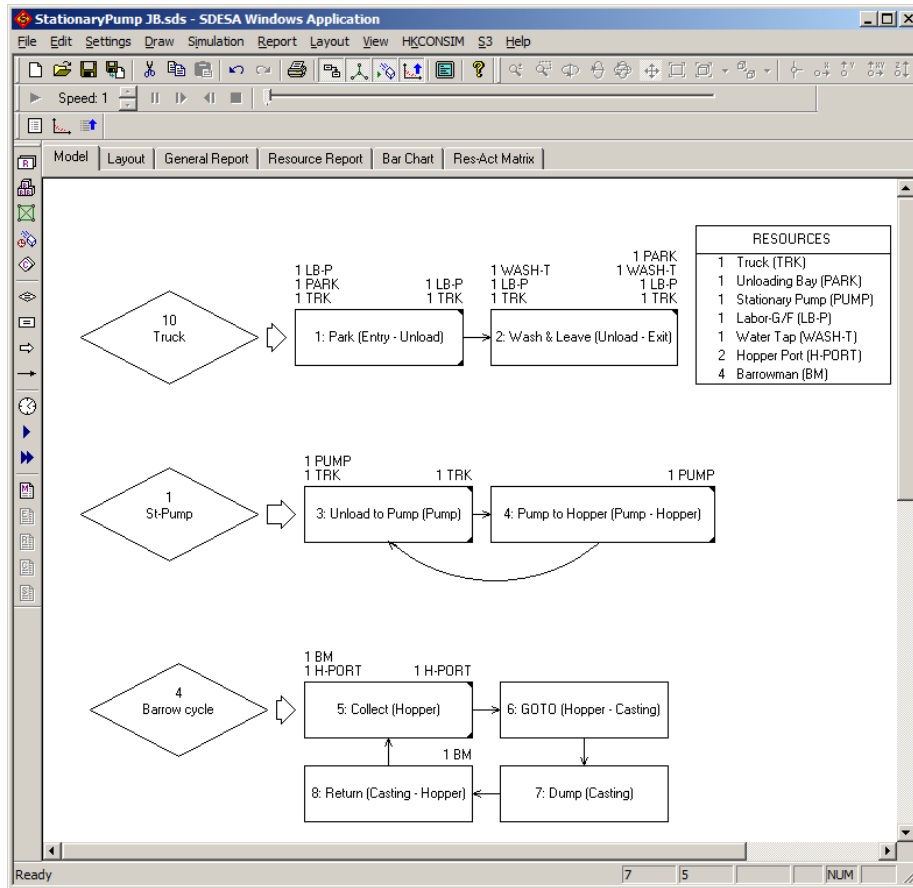
Based on the following two observations, SDESA is a good system to consider as a modeling tool for construction operations:

1. Since SDESA uses AD task representation, you only see the tasks in the model graphic, making it easier to read than the ACD notation of other systems. ACD models have resource logic as part of the graphical representation which affects the reading and understanding of the model. Lu et al [9] report that building models in SDESA takes less time than those based on CYCLONE modeling techniques (ACD-based), as SDESA's design (AD) allows for easier manipulation of model elements than an ACD system.
2. SDESA is construction-specific, so under most circumstances it is easier to use than a general purpose modeling software. Lu and Wong [10] indicate that SDESA construction models are built with more ease than with PROMODEL, a leading general simulation system.

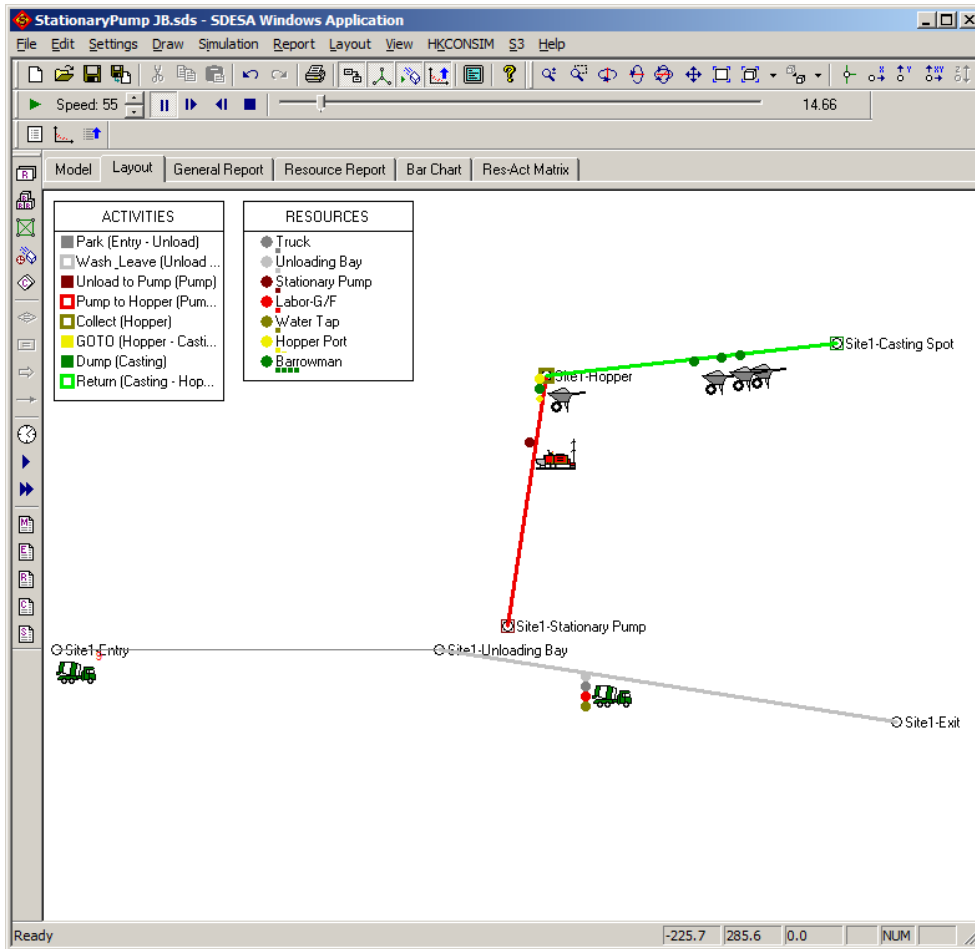
Accordingly, SDESA was selected as the simulation system for this introductory paper.

### **Some Details about SDESA**

SDESA has a "model" window where the model is assembled and a physical space ("layout") window where the animations occur. An example of a model implemented in SDESA is shown in Figure 2. The physical space or layout window for this model is shown in Figure 3. In this model, trucks deliver concrete to a pump, which pumps to a hopper. From there the concrete is placed using wheelbarrows. Variables are used to ensure that the pump is empty before accepting concrete, and that the hopper has enough concrete before filling the wheelbarrows.



**Figure 2 – SDESA Pump Model**



**Figure 3 – SDESA Pump Model Layout Showing Flow Paths**

In SDESA, flow units start the processes. In the model shown in Figure 2, that would be the “diamonds.” The name of the flow unit is shown along with the number of flow units in parentheses: Truck (10 ea.), St-Pump (1 ea.) and Barrow cycle (4 ea.). These flow units go into the model and look for tasks to perform. The tasks then look for available resources. The animation is done through the movement of the flow units in the Layout window.

Note that the St-Pump and Barrow cycle flow units are in a “flow unit cycle” (follow the logic arrows) in the model, whereas the Truck units are not. This indicates that once the 10 Truck units are processed, there won’t be anymore units to process for the Truck activities (Task 1, Task 2), and the simulation stops.

Also notice that the flow unit “Truck” (representing a full concrete truck) and the resource “TRK” are different entities. One is a “flow unit” that executes logic, while the latter is a resource to be used by the flow unit.

In SDESA, defined resources are shown in the RESOURCE box (see Figure 2). This table indicates that there are 4 Barrowman (BM) available and that the hopper has two ports (H-PORT) available. For each task, the required resources are listed on the top left corner of the activity box, and the resources released (upon completion of the task) are listed on the top right corner of the activity box.

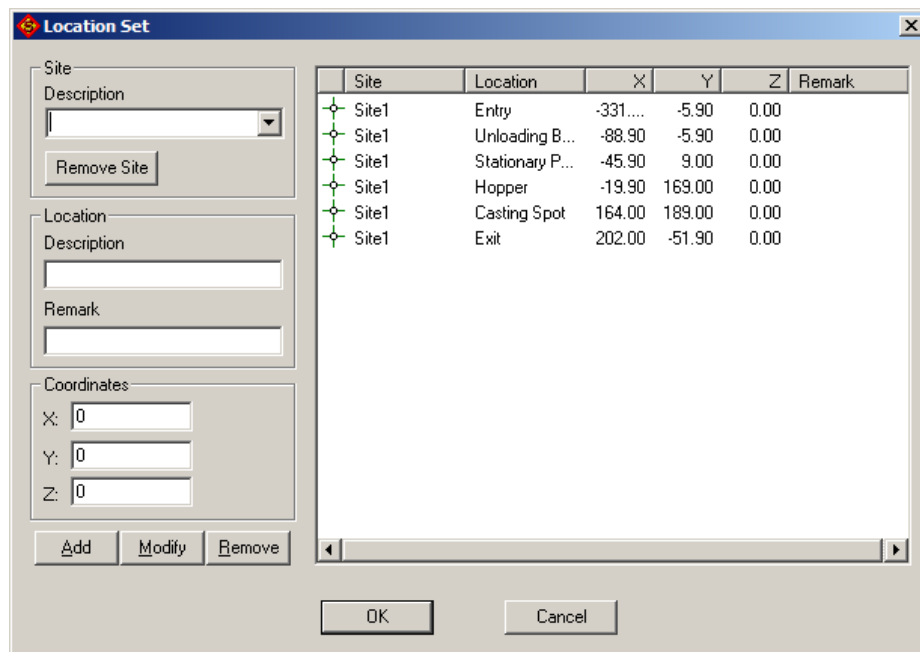
Without describing the whole model, some of the model’s resources and uses are listed next. For example, activity “5. Collect (Hopper)” requires 1 BM and 1 H-PORT resources before it can start (the hopper also needs to



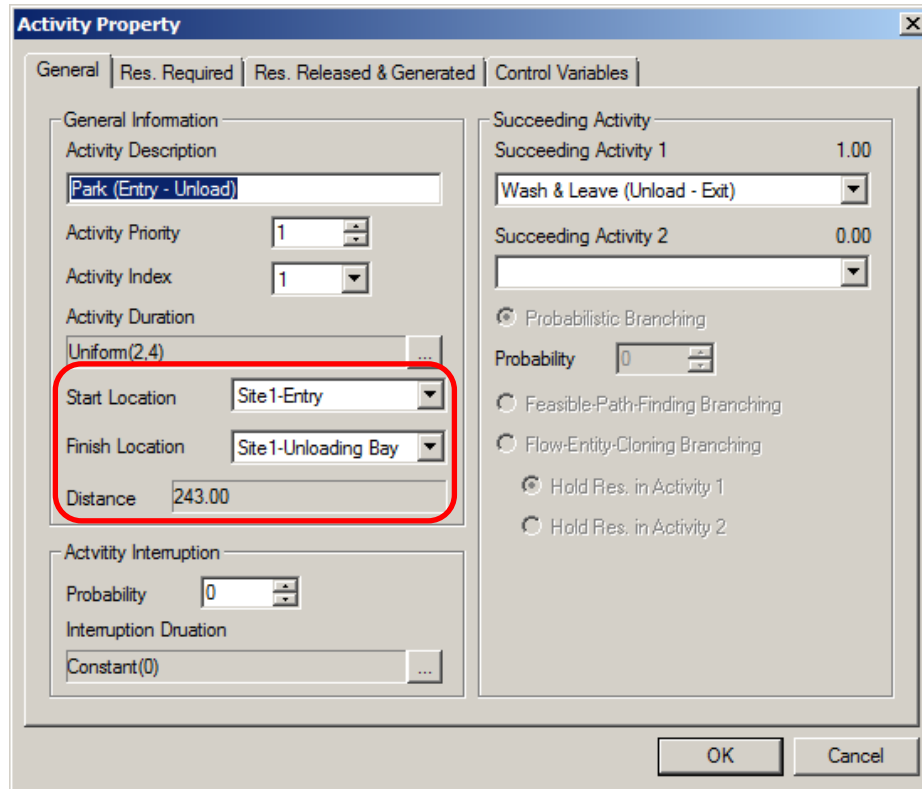
have concrete), and once it starts (when both of those resources are available) and finishes, it releases 1 H-PORT, keeps the 1 BM and the amount of concrete in the hopper is reduced. There is one truck (TRK) defined in the model (see RESOURCES box). This TRK is used for Task 1, Task 2 and Task 3. There is also only one loading bay or parking spot (PARK). This PARK is used for Task 1 and released in Task 2. Once released by Task 2 it can be used again by Task 1. Before Task 3 can start, PUMP and TRK need to be available. This illustrates how SDESA represents the interaction among resources in a model and how operations models generate activities. In this case, 2,072 activities were generated (listing not shown), based on logic involving only eight tasks.

Since TRK is limited to one unit and one TRK is required for 1: Park, 2: Wash & Leave and 3: Unload to Pump, only one Truck flow unit will be in the system at any one time. However before Task 2: Wash & Leave can start it must capture 1 WASH-T (water tap), 1 LB-P (laborer), 1 TRK (truck) and, in addition, it must have an empty truck (this is done through variables).

The connection between the model and physical map or layout is made via a table (Figure 4) that relates task location information in the Activity Property window (Figure 5) to the XYZ coordinates of the layout (Figure 3).

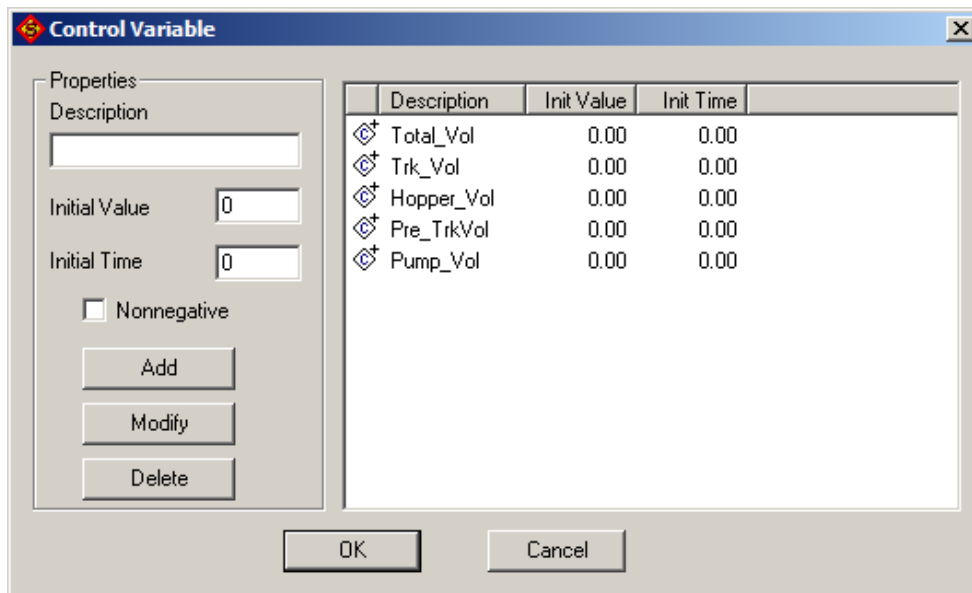


**Figure 4 – Table Mapping Location to XYZ Coordinates in Layout**



**Figure 5 – Activity Property Window – showing Start and Finish Location Used in Location Map Table**

SDESA has the ability to use variables during simulation, which are used in the model's logic. The variable definition table is seen in Figure 6.



**Figure 6 – Variable Definition Table**

## **Possible Improvements to SDESA**

While SDESA is very promising, below is a list possible improvements for SDESA.

### **Documentation**

The existing documentation is sufficient for simpler cases, but lacks detail on how to model certain constructs. For instance, the Activity Property Window (Figure 5) has several tabs: General, Res. Required, Res. Released & Generated and Control Variables. The documentation needs to explain in more detail how all the options and parameters in the tabs work, and provide how-to examples. The way around these limitations is to take an existing model and study it to see how the model works and how variables are used in the model's logic.

### **Flow Unit Attributes**

Most simulation models make use of "attributes" associated with an individual flow unit. For instance, truck no. 2 is carrying bricks, while truck no. 3 is carrying concrete. The routing (where the trucks go in the model) may be different depending of the type of load. How to assign attributes to flow units is undocumented in SDESA. Variables are model-wide and could be used to track, for instance, how many bricks have been delivered to the job site.

### **Resource Animation**

The SDESA design as-is, where animation is done through the flow units, should be sufficient to represent most construction processes. This is part of its simplicity. But, to give SDESA more flexibility, the developer should consider animating resources as well.

### **Limited Icons and Graphics**

Other simulation software have the ability to create icons or to import tables of icons. SDESA has only a limited set of icons and does not possess the ability to create or import icons or graphics to be inserted in the layout window, thus decreasing the ability of the model to communicate behavior to the analyst or observer. Additionally, other simulation software allow the user to change the icons during simulation ("empty truck" to "full truck"), change the icons colors or orientation during simulation, or to change shapes in the model's physical space. This ability adds to the improved visualization of the simulated process. For example, poured sections could turn brown, while those not poured could remain gray.

### **Display of Statistics and Graphs**

While the simulation is running, these displays could indicate how many loads have been processed or how long a at a certain certain queue is. These graphs or clock displays could be superimposed on the layout, displaying throughput, waiting times and queue length at a particular location, while the simulation is running. These are not available in SDESA.

### **Model and Space**

SDESA has a modeling window and a model's physical space or layout window where the simulated activities are observed. In other simulation systems the model is created right on the model's physical space or layout, thus forcing the modeler to be more cognizant of constraints imposed by physical space. As is, some operations in the model may not have a physical space counterpart.

## Automatic Generation of XYZ Locations for Certain Standard Processes

This idea needs to be refined and developed further before its implementation is considered. When modeling a linear process (railroad or pipe laying) or a vertical process (highrise frame) the modeling system should be able to generate activities and their respective position in XYZ space, with the modeler having only to define the basic activity. The modeler would define the length of the pipe and what is needed to lay pipe (excavate, set, backfill and equipment moves), and the system would generate the XYZ coordinates for the number of pipes to be installed, and it would also generate the related tasks. “Pipe 2 excavation” would be shown in the space for the second length.

## Linking to Building Information Modeling (BIM) 3D Models

It should be possible to link the simulation output to a BIM model, just like CPM networks are linked to 3D models in order to produce animations of construction progress. This would result in a more realistic depiction of a process. The animations would also involve the animation of materials handling and placement.

## Commercialization and Distribution

For SDESA to succeed as a mainstream modeling tool for the construction industry, the developers need to have an on-going product strategy. In the meantime, the developer needs to make the product available and distribute the product as-is with proper caveats and licensing requirements. An alternative would be to have a group of developers and users that would manage the versions, product documentation, quality control checks, and product licensing and distribution. As part of the strategy the developer needs to implement SDESA training sessions as well.

## Modeling the Laying of Pipe

Having briefly introduced the reader to operations modeling, simulation, SDESA and the modeling process, the next step is to show how a simple pipe laying operation is represented in SDESA.

### The Models

A model to represent a process that installs 2,499.4 m (8,200 LF) of pipe will be assembled. The process consists of excavating, lowering and setting the pipe, and backfilling. Two models were implemented in SDESA. Model A uses 12.2 m long pipe, with an excavator to lower the pipe into the ditch (Figure 7). Model B uses 6.1 m long pipe that can be lowered manually by the pipe laying crew (Figure 8).

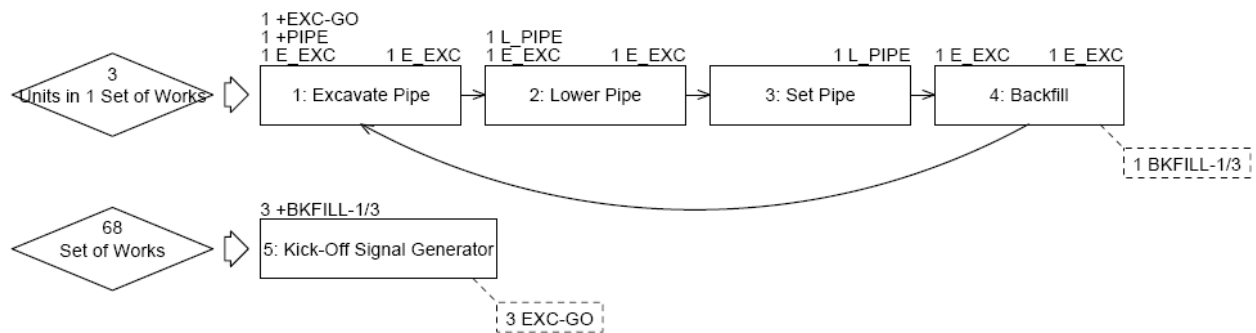
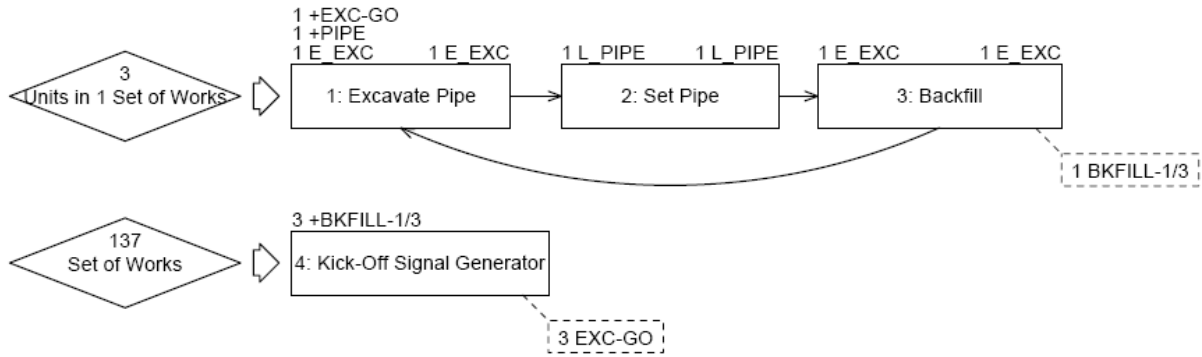


Figure 7 – Model A – Use 40 ft (12.2 m) long pipe, 205 ea.



**Figure 8 – Model B – Use 20 ft (6.1 m) long pipe, 410 ea.**

Task durations for the two models are shown below (Table 1). Note that the durations for Model A are longer, as the time to excavate, set and backfill a 12.2 m section of pipe is longer than for a 6.1 m section of pipe. Table 2 shows the relationship between tasks and resource usage (how many resources are needed to perform the task). The “Kick-Off Signal Generator” task is used to “pace” the simulation so that, at most, three pipe lengths are excavated, set and backfilled at a time. This prevents the excavator from excavating the length of the pipe run without setting any pipes.

<b>Model</b>		
<b>Tasks</b>	<b>A</b>	<b>B</b>
Excavate	30	20
Lower Pipe	10	n/a
Set Pipe	30	20
Backfill	30	20
Total Duration	100	60

**Table 1 – Task Durations (min.)**

<b>Model</b>			
<b>Tasks</b>	<b>Resource</b>	<b>A</b>	<b>B</b>
Excavate	Excavator	1	1
Lower Pipe	Excavator	1	n/a
Lower Pipe	Pipe Crew	1	n/a
Set Pipe	Pipe Crew	1	1
Backfill	Excavator	1	1

**Table 2 – Resource Requirement for Each Task**

The difference in these two models is that in Model A, task 2 (“Lower Pipe”) and task 3 (“Set Pipe”) have been replaced in Model B by task 2 (“Set Pipe”). Note that in SDESA, the resources needed for starting a task are listed in the upper left corner of the task box. Upon completion of a task, resources that are released are listed in

the upper right corner of the task box. In Model A, task 2 (“Lower Pipe”) needs one L\_PIPE (labor) resource and one E\_EXC resource (equipment) before it can start. When the task is done, it releases one E\_EXC, which means the L\_PIPE resource is still with the pipe, so that it can be used for task 3 (“Set Pipe”). The convention used in the naming of resources is: “L\_” for a labor crew (pipe laying crew) and “E\_” for an equipment resource (the excavator). The number before the resource name is the number of units of the resource that are used or released by the task.

In order to vary one of the parameters in Model A, a copy was made with only one change: the copy will have *two* E\_EXC (excavators) available. The copied model is Model A2, while the original is Model A1. Table 3 summarizes the *available* resources for the tasks in each model.

Note that a physical layout of these models is not being presented.

<b>Model</b>			
<b>Resource</b>	<b>A1</b>	<b>A2</b>	<b>B</b>
Excavator	1	2	1
Pipe Crew	1	1	1

**Table 3 – Number of Resources Available**

**Model Performance**

Which configuration should the project use? Model B has to install twice as many sections of pipe as in Model A1 (410 vs. 205), while the overall process duration is Model B is about half of Model A1’s (60 min. vs. 100 min., see Table 1).

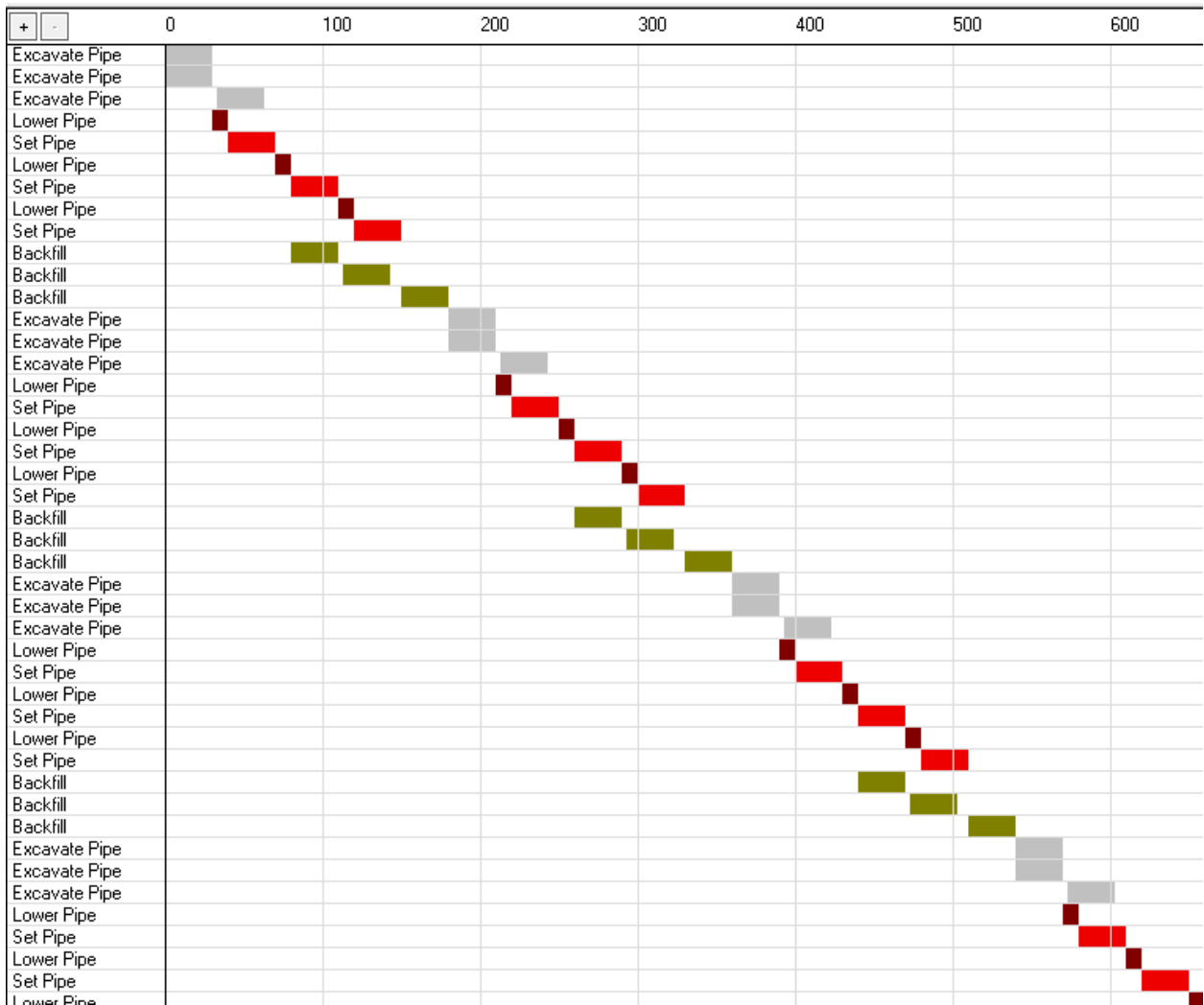
The second Excavator in Model A2 should lower both excavators’ utilization rate, as they will be waiting for work more often. In Model B, the utilization of the excavator should be close to 100%; while the pipe crew is installing pipe, the excavator can be backfilling the previous pipe, so that it is always either excavating or installing. Table 4, Table 5 and the Model Output Bar Chart (Figure 9) list the reported performance by SDESA of these models.

<b>Model</b>			
<b>Statistic</b>	<b>A1</b>	<b>A2</b>	<b>B</b>
Overall Time (min.)	19,276	12,340	18,038
No. pipe (ea.)	205	205	410

**Table 4 – Overall Installation Statistics**

<b>Model</b>			
<b>Resource</b>	<b>A1</b>	<b>A2</b>	<b>B</b>
Excavator	79%	60%	100%
Pipe Crew	42%	67%	52%

**Table 5 – Resource Utilization**



**Figure 9 – Task List Generated by SDESA for Model A2**

A simulation model may be considered a “task generator” based on the model’s logic and parameters (see Figure 9). These tasks are the same ones represented in the model. In SDESA’s bar chart (above), each task is automatically given a different color, so all “Set Pipe” tasks are red. This is a list of tasks that must be done by the model’s resources in order to accomplish the desired result: lay 205 sections of pipe.

### Decision Making Considerations

Model A1 should be chosen if the overall installation time of 19,276 min. is within the parameters of the construction plan and is a less expensive configuration than Model A2. Model A2 offers much better performance (12,340 min.), but at a cost. The second excavator’s operating and maintenance cost would have to be balanced with the expected reduction in installation time (6,936 min.) and overall project goals.

Model B provides a small time gain over Model A1, but this could be a significant difference for a particular project. It is also a simpler operation as there is no need to use the excavator to lower the pipe.

The selection of a particular configuration would depend on the particular cost and scheduling constraints present in a project.

### **Practical Conversion into Working Days**

If the effective productive hours per day are 7.5 hours, then the work day duration expected from Model B with an installation time of 18,038 min. is 40 work days (205 LF/day or 62 m/day). Because the simulation did not account for weather or maintenance, the simulated duration should be modified to account for these. If five days for weather and three days for maintenance are to be added, the expected duration for this operation in a schedule should be set to 48 working days.

### **Simulation as a Tool**

In an actual infrastructure project with 2,499.4 m of pipe to install (same quantity as in the models presented here), the duration for this activity in the submitted schedule was listed at 125 work days. The observed installation rate was recorded at 62 m/day (without any weather or maintenance interruptions), the same as Model B's rate. This discrepancy forced the project team to look more closely at the project assumptions and to question the contractor's schedule value as a predictor of future performance. Simulating this operation before starting it would have resulted in the project team using a more accurate duration for this activity in the schedule.

### **Other Implementations of Operations Models**

There are several examples of the useful implementation of simulation in actual construction projects. Here, three models are discussed. Two models used SDESA: one was implemented in China and the other one in Hong Kong; the third used a similar system to CYCLONE, CYREN, and was implemented in the United States.

#### **Bird's Nest Stadium**

Chan, Lu and Zhang [11] simulated steel erection operations for the Bird's Nest Stadium used during the Beijing Olympics. The model was used to experiment with different sequences steel columns and frames installation: clockwise, counterclockwise or by column height, and then installing all columns, and then all roof frames. The model also considered different start times for occupying the different assembly areas, as available site space was a main constraint in scheduling the tasks by different subcontractors. A total of 18 scenarios were considered. The one statistic driving the method selection was the overall installation time for the work, which inherently meant shortening the travel distance of the 800-ton crawler crane through the entire installation process. The sequence with the shortest duration was the one where sectors were built by increasing column height, and was the one recommended for the contractor to follow.

#### **Lowest Cost Accelerated Alternate Bid**

As consultants for a contractor in the U.S., Halpin and Berrios [12] optimized formwork and crane usage for a stadium bid. Simulation in this case was used to select a scenario from twenty form-crane combinations that would result in the lowest cost accelerated option. For the accelerated alternate, the submitted bid was the lowest; however because of funding, the project was awarded to the contractor that submitted the lowest cost alternate "normal" duration bid.



## **Elevated Viaduct in an Urban Setting**

For an elevated viaduct project in Hong Kong in a congested urban setting, the storage and handling of precast segments was very relevant to the efficiency and schedule of the project [13]. In most cases, staging areas under the working span were very restricted, setting the stage for mishandled materials and productivity losses. Simulation was applied to answer these questions: (1) How far away should a remote storage area be? (2) How many precast segments should be stored there? (3) How many tractor-trailers would be needed? The simulation tested the sensitivity of the installation cycle time to changes in these factors (questions), evaluating a total of 17 scenarios. The base scenario did not consider a remote storage area. The simulation results were summarized in guidelines the contractor would follow, depending on the availability storage space under the work area and the availability of remote storage areas. The recommended guidelines were as follows:

1. Store all 14 segments under working span, using two tractor-trailers, if space allows.
2. If space under the working span is restricted and not all segments can be stored there, consider the following:
  - a. If available, use a remote storage area located within 25 minutes of the working span, using two tractor-trailers.
  - b. If a remote area within 25 minutes is not available, find one within 45 minutes of the working span, and observe the following:
    - i. Store up to four segments, and continue to use two tractor-trailers.
    - ii. If more than four segments need to be stored, then use three tractor-trailers.

## **Conclusion**

The modeling of construction operations has been facilitated since the introduction of CYCLONE in 1973. While the modeling of operations and simulation has been used widely in manufacturing, transportation and other industries, the adoption of simulation in construction has been very slow, even though the methodology has benefits. Simulation results can be used to assist in making decisions regarding crew make-up, durations, sequences, methods and operational efficiency improvements.

Because of its relative ease of use and construction-oriented modeling environment, SDESA was used to introduce the reader to simulation via a simple pipe-laying process, where the basic modeling elements were shown, as well as output generated by the simulation of the models. These statistics were used to analyze the models and to make suggestions regarding which model or configuration would be suitable for a particular purpose. In addition the simulation provided information in regards to the expected duration for the process being modeled. This model, its output and analysis show that simulation can describe an operation's behavior and provide parameters for decision-making, estimating and scheduling.

The paper highlights three projects where simulation was used successfully to assist decision-makers. In each of these applications, simulation provided the analyst with a decision-support framework. The Bird's Nest Stadium simulation evaluated many approaches, recommending one that shortened the overall installation time. For the accelerated construction time stadium bid, simulation successfully provided a solution that was the lowest cost bid for the accelerated time frame. For the elevated viaduct problem, simulation provided a set of operational guidelines for the contractor to use.

Given these results and uses of operations modeling and simulation, and prior research indicating substantial productivity improvements where simulation has been used in construction, the construction industry should become more familiar with this tool, and ramp up its use given its potential benefits.

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