

## **Synchronize Operations Modeling and Site Layout Modeling by Augmenting the Simplified Discrete-Event Simulation Approach (SDESA)**

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### **Abstract**

It is crucial but challenging for a construction planner to place multiple dimensions into perspective (i.e. time, space, resource, and cost, along with the 3D physical definition of structures) for describing and optimizing the complicated, interactive, and dynamic construction processes. The augmented SDESA represents an enhanced version of the simplified discrete-event simulation approach (Lu, 2003) and its computer platform. The augmented SDESA allows the spatial definition of a construction system in a 3D graphic environment, and provides a simple and cost-effective means for modeling operations in a dynamic construction system, synchronized seamlessly with the 3D construction site layout planning. The major benefit is the increased similarity of the model to the actual system being simulated. As such, the accuracy, reliability and predictability of the model are significantly improved. The augmented SDESA also features the 3D animation for post processing the simulation so as to help the user visualize and analyze the simulation results. A "Hoist and Barrow" concreting model, which was set up based on a local building site, is presented to illustrate the capabilities and features of the augmented SDESA.

### **Keywords**

Construction planning; Simulation; Site layout; Visualization; Animation.

### **1. Introduction**

Detailed construction operations planning requires organizing and coordinating, spatially and temporally, the available resources of workers, machines, and materials, and workface spaces in an efficient and cost-effective fashion so as to fulfill the time, cost, and quality objectives of a given project. Therefore, it is crucial but challenging for the planner to place multiple dimensions into perspective (i.e. time, space, resource, and cost, along with the 3D physical definition of structures) for describing and optimizing the complicated, interactive, and dynamic construction processes.

The present common practice of construction planning is the use of a critical path method (CPM) based schedule in the form of an activity-time 2D bar chart (Gantt chart) on both long term (i.e. the whole project period) and short term basis (i.e. the month/week ahead or even particular days). Nevertheless,

lack of resource and spatial considerations in a CPM plan has resulted in the difficulty of identifying mistakes of the construction plan and the inconsistency of interpreting the project schedule (Koo and Fischer, 2001). CPM plans brought about little real savings but “unrealistic specifications, disputes, and dispute resolutions based on incorrect data in the construction industry” (Fondahl 1991). To overcome the CPM’s drawback, seasoned site managers informally rely on judgment, intuition, and experience to mentally coordinate the resource and work space requirements with the use of the bar chart schedule. As a result, the bar chart plans are often annotated with resource and location data.

Operations simulation has been proven as an effective tool for engineering complex construction processes that feature dynamic queuing and resource interactions. Simulation models consider the discrete temporal events that occur during the construction operations (e.g. the transition between active and idle states of different resources). However, the spatial definition of a construction system, such as the site layout design, the location of each activity, the location of resources, is by and large ignored in the existing simulation models. The methodology of discrete event simulations simply represents spatial changes with certain temporal events associated.

To synchronize operations modeling with site layout modeling, this paper presents the augmented SDESA, which represents an enhanced version of the simplified discrete-event simulation approach (Lu, 2003) and its computer platform. The augmented SDESA allows the spatial definition of a construction system in a 3D graphic environment. The major benefit is the increased similarity of the model to the actual system being simulated. As such, the accuracy, reliability and predictability of the model can be significantly improved. With the newly developed computer tool of the augmented SDESA, the 3D animation for playing back the simulation is also realized so as to help the user visualize and analyze the simulation results.

## **2. Review of Simulation with 3D Graphics and Animation**

Recent research efforts have responded to practitioners’ needs for improving the knowledge-intensive and ill-structured process of construction planning. To complement the CPM/bar chart schedules, “4D” models inextricably integrated the temporal and spatial aspects in construction planning by linking 3D CAD graphic images to the fourth dimension of time (Koo and Fischer, 2000). Real site management features, such as quantity takeoff, analysis of resource requirements, cost evaluation, and generation of site layouts, were also added to 4D modeling (Zhang et al, 2000). Daewood et al (2003) coupled AutoCAD with MS Project into a 4D system called the Virtual Construction Site (VIRCON), which drew on a MS Access database for organizing the resource/process information. A 3D model of the construction product (e.g. a building) was setup in AutoCAD and all its components were connected with the resource scheduling database. So the user could visualize the simulation of construction operations by continually refreshing the computer screen with AutoCAD drawings. One limitation with current 4D CAD systems is their dependence on the CPM software packages (MS Project or P3) for scheduling. Thus, the visualization of the construction operations is limited to rendering layers or blocks of a building in CAD, synchronized with the CPM schedule periodically (daily, weekly, or monthly). The 4D modeling, in general, does not consider the dynamic interaction of various resources in constructing or installing the components of a building, as does the discrete-event operations simulation modeling [such as the CYCLONE methodology (Halpin and Riggs, 1992)]. Kamat and Martinez (2001) developed a 3D visualization system called the Dynamic Construction Visualizer (DCV). The DCV was not a simulation tool itself, but designed as a “postprocessed” visualization tool that could be linked to an operations simulation system for playing back the realistic motion of equipment/labor resources and displaying the dynamic construction operations. The DCV provided a concise yet powerful set of animation commands. It possessed the ability to process sequences of these commands generated by simulation models such that the dynamic states of modeled systems were depicted. The use of the DCV started with running a simulation model and generating the animation trace file in the syntax of the DCV language. The DCV

then graphically illustrated the operations being modeled by processing the trace file sequentially. Nonetheless, the “states of completion on a constructed facility can only be depicted in a local area”, so it is impractical to model all the operations for an entire construction project with DCV (Kamat and Martinez, 2001). Shi (1999) introduced the Activity-Based Construction modeling simulation (ABC), which is an activity network-based modeling and simulation method using one single element (e.g. activity) for modeling general construction processes. The ABC system provides the iconic animation function to visualize the simulation results on the computer screen (Zhang et al, 2003). This system uses different icons for representing different kinds of resources. The animation takes advantage of the activity-based network diagram as background, and the connecting arrows as the moving path for the resource icons. Another related development was to link simulation models for heavy earthmoving construction with 3D CAD in an attempt to streamline the modeling process (AbouRizk and Mather 2000). The construction information including product information (facility to be constructed or components), the construction resources utilized, the construction methods, can be specified, captured and transformed within a Microstation CAD environment in order to facilitate the building of a SLAM simulation model. Yet, the fact that location or space was not explicitly treated in operations simulation constrained the visualization of simulation models through 3D CAD integration.

### **3. The Augmented SDESA**

The augmented SDESA is a recent research product for construction operations simulation developed at the HK Polytechnic University. The original SDESA streamlined both the simulation algorithm and the model structure. The executive program of SDESA controlled the simulation operations by manipulating two dynamic queues, namely, the flow entity queue and the resource entity queue (Lu 2003). Note that simulation entities are the elements of the system being simulated and can be individually identified and processed (Pidd 1989). Flow entities, passing through a sequence of activities in a process, are elements for invoking activities. They shared mutual time attributes (such as arrival/departure times at an activity) and act as a boundary constraint to control the number of times an activity is invoked. In addition to the reusable resource entities (such as equipment/crew resources), the SDESA also distinguishes disposable ones for representing those intermediate products or command units that can be used once only (Lu 2003).

To incorporate site layout planning into simulation, new features and functions were added in developing the augmented SDESA. A site layout view enables the modeler to sketch a site layout plan within SDESA. Location attribute are attached to resource entities for tracking their positions and movements between different processes/activities in the simulation process. The animation function allows the modeler to play back a simulation experiment and visualize the dynamic site operations on screen (e.g., showing the current activities, the movement of flow entities, and the utilization of resource entities). The new features for site layout planning and the animation functions greatly enhanced the functionality of SDESA simulation. Hence, the augmented SDESA holds potential to provide accurate and comprehensive decision support to practitioners in achieving efficiency and cost-effectiveness through better planning.

#### **3.1 Site Layout Planning**

The augmented SDESA computer platform provides a 3D environment for design and visualization. It features a graphical interface and some useful tools to help the user view, design, and modify the geographical layout of a system. For example, the zooming and rotating tools provide the modeler with the flexibility to adjust the zoom scale and aspect of the site layout. The 3D space is discretized into key locations that are of relevance to construction planning. Hence, the main task of site layout planning within SDESA is to specify locations for construction activities (including the start and finish locations), and the resources' initial locations. SDESA allows the user to (1) drag and drop location icons in its 3D layout view, (2) tag each location with textual descriptions, and (3) enter the 3D coordinates of each location. The user can even define more than one sites in SDESA's site layout view; each site consists of

its own location set. For instance, to model the one-plant-multi-site ready-mixed concreting construction system, one central batch plant and several building sites distributed over a large area can be readily laid out in SDESA.

### 3.2 Definition of Augmented SDESA Model

The augmented SDESA includes the dimension of space/location for defining a simulation model. Therefore, in addition to the activity duration and resource requirements, the definition of an activity involves specifying (1) the start and finish locations for a transportation activity to span or (2) the location where a production activity occurs. The locations of the resource entities, which are contained in the resource pool of a SDESA model, should also be initialized. The augmented SDESA adds a new modeling object of “site resource transit information system” for the modeler to define the transit duration required for individual resources to move from one location to another; the data include the start and finish locations, resource type and transit time. Similar to the activity durations, the transit time can be constant or represented with statistical distributions. To assist the modeler in estimating the transit times, the the SDESA automatically calculates the straight-line distance between two locations.

Alternatively, the augmented SDESA allows the modeler to define locations together with activities and resources in its 3D graphical environment. Activities are represented with a line segment linking the start and finish locations. If the start and finish locations are identical, a tiny rectangle will be used to symbolize the activity instead. For visual clarity, different activities are drawn in different colors. By dragging and moving the start and end point of these “activity” lines or the “activity” rectangles, the user can easily manipulate activity locations and build a SDESA model. Similarly, the start location of resource entities, as represented with icons, can be initialized within the 3D layout view.

### 3.3 Simulation

The augmented SDESA accounts for the time delay for moving a resource from location to location. During the simulation, the activity selects the required resources with the earliest arrival time (RAT) at the location of the current activity, instead of using the ones with the earliest ready-to-serve time as in the original SDESA. Activities will not be processed until all the required resources arrive at the required location. With this modification, unnecessary resource movements will be avoided to achieve efficiency and cost-effectiveness. This mechanism for resource allocation is devised following the general practice in the construction sites. The begin time of activity (BT) can be determined with the equation given below:

$$BT = \max \{AT, RAT(i)\}, i \in (\text{resource\_entities\_involved})$$

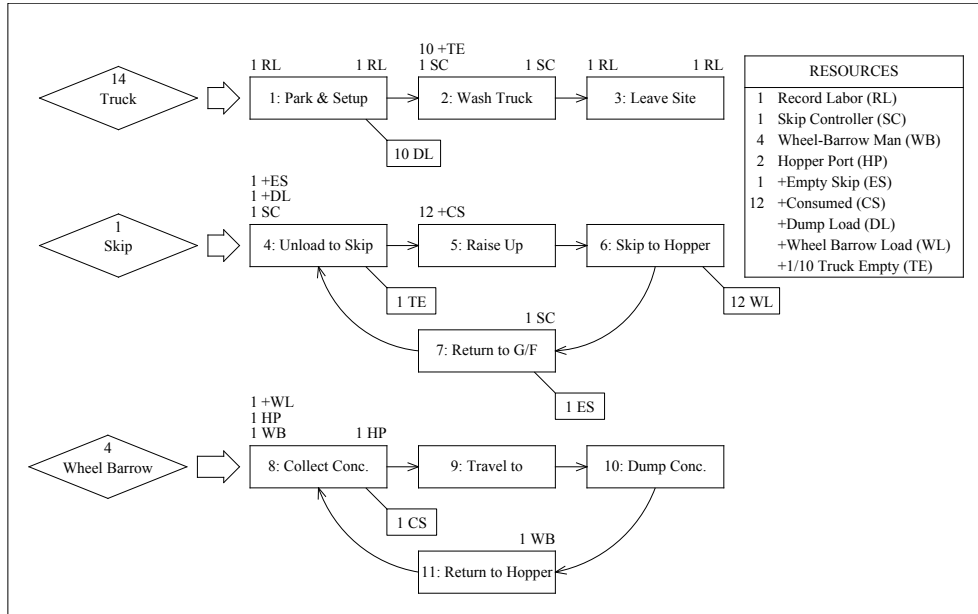
Where  $RAT(i)$  is the arrival time of the  $i^{\text{th}}$  resource entity involved in the activity and  $AT$  is the arrival time of a flow entity. At the end of the activity, locations of both the flow entity and reusable resource entities released by the activity will be set as the finish location of the current activity.

### 3.4 Animation

The animation function of the augmented SDESA postprocesses the simulation results and plays back the simulated operations. To produce an animation, the modeler selects different icons from an icon image library of the augmented SDESA to represent different flow/resource entities in preparing the simulation model. Following the simulation analysis, the animation starts by placing the entity icons onto the 3D site layout background. The on-screen positions of those icons are continuously refreshed such that the real time locations of the flow entities and resource entities in the actual system are reflected dynamically. As the animation proceeds, icons of flow/resource entities move from one location to another along the line connecting the two locations in the site layout plan. When an activity is being processed, it will be highlighted with bold lines. In short, the animation provides a variety of dynamic information that is not

available from a numerical simulation experiment, so the modeler is able to visualize the construction activities more clearly and detect any logical inconsistencies or errors in the simulation model more easily. Next, a “Hoist and Barrow” concreting model, which is set up based on a local building site, is presented to illustrate the capabilities and features of the augmented SDESA.

#### 4. Case Study



**Figure 1: SDESA Model for Hoist and Barrow Concreting Operations**

The typical “Hoist and Barrow” concreting method uses a hoist for vertical transportation of concrete in a skip. To begin with the concreting operation, a truck-mixer filled up with ready mixed concrete arrives at the site and parks close to the feeding tip of the skip. Then, the truck-mixer unloads concrete into the skip to its full capacity. Upon receiving a “request concrete” signal from the upper floor, the skip controller switches on the hoist at the ground level. When the skip reaches the upper floor, it stops at the opening of a hopper, turns up-side-down toward the hopper, and dumps the concrete into the hopper. Keeping inclined for several seconds, the skip turns upright again and moves back to the ground level. Upon receiving another “request concrete” signal, the unloading process at the ground level repeats, and the next skip-load of concrete will be hoisted. When the hopper at the upper floor is refilled, the laborers maneuvering wheelbarrows (barrowman) start collecting concrete one after another and pour the concrete into the formwork of a slab by traveling along some temporary timber paths. The barrowman’s work cycle can be readily identified, i.e. collecting concrete into wheelbarrows, traveling to the pour destination, placing concrete, traveling back to the hopper, and collecting concrete from the hopper again. Once the hopper is becoming empty, the barrowmen just press a bell button to alarm the controller at ground level, requesting another skip-load of concrete. After the truck-mixer is emptied, it leaves the unloading bay and moves to the washing bay, where the truck is cleaned before departing from the site.

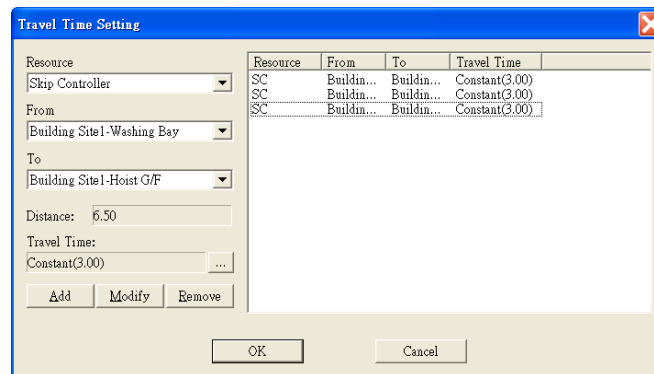
Fig. 1 shows the SDESA model for the “Hoist and Barrow” concreting operation. Note that the flow entities to be processed are symbolized with a diamond and the activities with a solid rectangle. The predecessor/successor activities are connected with arrows. The resource entities requested by each activity are marked on the top left corner of the activity rectangle, while the resource entities to be freed at the end of the activity are marked on the top right corner. The disposable resource entities generated are shown in the dashed rectangles to the bottom right corner of the activity rectangle. The “plus” sign before

the resource name serves to mark disposable resource entities. Key locations on the site relevant to the operations have been discretized into a site-level 3D coordinate system [such as the truckmixer awaiting area, the hoist stations at the ground floor (G/F) and at the upper floor (U/F), etc.]. The input models for activity times (in the forms of constants, uniform distributions, or beta distributions) along with the start/finish locations of each activity for the base case scenario are given in Table 1.

Activity	Duration Input Model					Start Location	Finish Location
	Type	L	U	a	b		
1. Park & Setup	Uniform	1.5	3.5			Awaiting Area	Unloading Bay
2. Wash Truck	Uniform	2	2.8			Unloading Bay	Washing Bay
3. Leave Site	Uniform	0.5	1.25			Washing Bay	Site Exit
4. Unload conc.	Beta	0.3	0.9	0.6	1.9	Hoist G/F	Hoist G/F
5. Raise Up	Constant	0.1				Hoist G/F	Hoist U/F
6. Skip to Hopper	Constant	0.14				Hoist U/F	Hoist U/F
7. Return to G/F	Constant	0.1				Hoist U/F	Hoist G/F
8. Collect Conc.	Beta	0.1	0.4	1	3.2	Hopper Port	Hopper Port
9. Travel to	Beta	0.2	0.4	10.2	10.3	Hopper Port	Dump Area
10. Dump Conc.	Beta	0.03	0.18	4.2	5.2	Dump Area	Dump Area
11. Return to Hopper	Beta	0.2	0.4	1.4	1.7	Dump Area	Hopper Port

**Table 1: Activity Duration Input Models and Start/Finish Locations**

Two scenarios were considered: the base case scenario represents concreting the floor slab on the second floor (2/F) of a building, which is about 6 meters above the ground level; the second scenario runs the identical operation as in the base case except for the location of pour changed to the twentieth floor (20/F), which is about 56.4 meters above the ground level. As such, the z-coordinates for locations “Hoist U/F”, “Hopper Port” and “Dump Area” were adjusted from 6 meters as in the base case scenario to 56.4 meters as in the second scenario, with coordinates of other locations intact. Accordingly, the durations for moving the skip up and down the hoist (namely, activities “5. Raise Up” and “7. Return to G/F”) were modified from 0.1 minute (6 seconds) to 0.5 minute (30 seconds) by on-site measurement.



**Fig. 2: Site Resource Transit Information System Definition at Model Level**

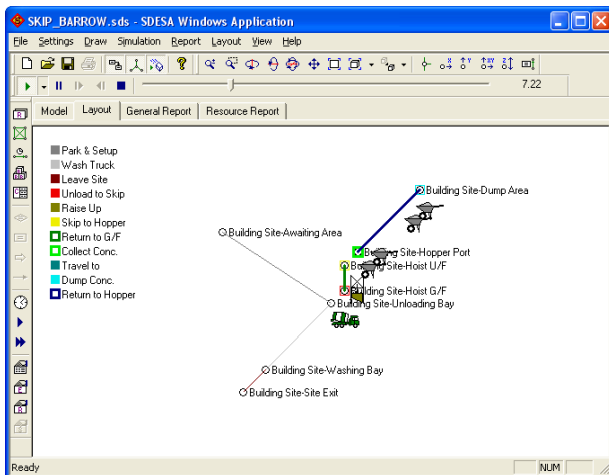
Noted from the simulation results of both scenarios is a 3-minute delay between the finish of the “Washing” truck-mixer activity and the start of the “Raise Up” skip activity. Such a delay is due to the requirement of the skip controller by both activities: after washing the truck-mixer, the skip controller’s current location was set as the washing bay (i.e. the finish location of the “Washing” activity given in Table 1), so the skip controller moved from the washing bay to the hoist station at the ground floor (i.e. the start location of the “Raise Up” skip activity) before initiating the hoist activity. The augmented SDESA automatically decides on the duration for a resource entity to transit from one location to another

on the site (such as the skip controller’s movement, or the hoist up and down the skip between ground and upper floor) by querying its built-in site resource transit information system, which is established when the user defines the simulation model (Fig. 2). The averaged “just-in-time” arrival times for fourteen truck-mixers are based on twenty independent simulation runs on each scenario, as shown in Table 2. The “just-in-time” arrival of a truck is defined as being right on the moment of time when the previous truck has just left the site, such that continuous concrete supply to the site can be achieved while reducing the truckmixers’ queuing on the site.

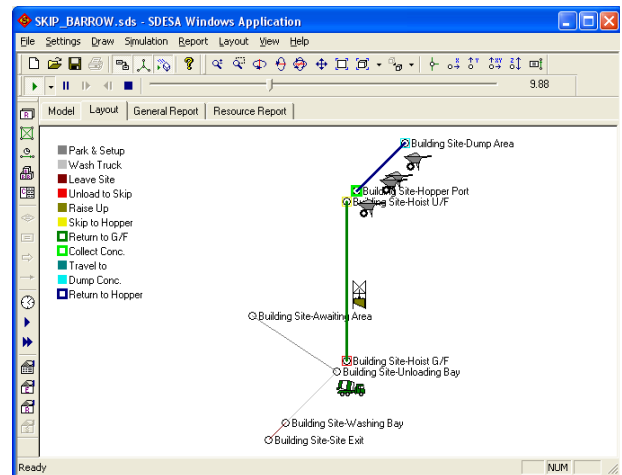
Truck-mixer	Just-in-time arrival time (min)	
	Basecase Scenario (2/F)	Scenario 2 (20/F)
Truck 1	0.00	0.00
Truck 2	31.71	38.99
Truck 3	55.04	62.66
Truck 4	82.34	91.71
Truck 5	109.11	121.15
Truck 6	136.25	150.62
Truck 7	162.59	180.33
Truck 8	189.37	209.83
Truck 9	216.21	238.78
Truck 10	242.42	268.75
Truck 11	269.97	298.56
Truck 12	296.25	327.58
Truck 13	323.06	356.42
Truck 14	350.48	385.69

**Table 2: Predicted Arrival Times for Two Scenarios**

The animation for the above “Hoist and Barrow” concreting simulation allows the modeler to visualize the dynamic process over the simulated time on a computer screen, including the locations and full/empty status for the truck mixers, the skip and the wheelbarrows. Fig. 3 and Fig. 4 give snapshots of the animations for each scenario respectively; both show three activities (namely, “Return to G/F”, “Collect Concrete”, and “Return to Hopper Port”) are being executed (as highlighted with bold lines) at the current moment. It is apparent that the dynamic information provided by animation can enrich the modeler’s understanding of the construction process and facilitate the validation of the simulation model.



**Fig. 3: Animation Screen Shot for Basecase Scenario**



**Fig. 4: Animation Screen Shot for Scenario 2**

## 5. Conclusion

Detailed construction operations planning requires organizing and coordinating, spatially and temporally, the available resources of workers, machines, and materials, and workface spaces in an efficient and cost-effective fashion so as to fulfill the time, cost, and quality objectives of a given project. Operations simulation has been proven as an effective tool for engineering complex construction processes that feature dynamic queuing and resource interactions. Yet, the spatial definition of a construction system, such as the site layout design, the location of each activity, the location of resources, is by and large ignored in the existing simulation models. The SDESA is augmented by incorporating new features for site layout planning and 3D animation. This has greatly enhanced the functionality of operations simulation and hence provide accurate and comprehensive decision support to practitioners in achieving efficiency and cost-effectiveness through better planning.

In the ongoing research, the SDESA is being tested on real projects to improve operations planning and site layout planning in an integrated approach, and will be further augmented to (1) model the random equipment breakdowns and regular activity interruptions, (2) allow continuous modeling functionality, and to (3) accommodate more flexible strategies for resource allocation and utilization as encountered in the real world. Interested readers may contact the first author for obtaining an evaluation version of the SDESA software plus the user's guide document.

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