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COMPARING PROMODEL AND SDESA IN MODELING CONSTRUCITON OPERATIONS

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ABSTRACT

The research presented applies the PROMODEL alongside a simplified discrete-event simulation approach (SDESA) and its software platform resulting from in-house construction research for modeling typical construction operations. The characteristics and modeling needs for construction and manufacturing systems are compared in general. A simple earth-moving operation and a real site operation integrating concreting and waste handling practices serve as case studies to illustrate the features, advantages, and limitations of PROMODEL and SDESA. It is found that SDESA can adequately, precisely depict the construction operations with much less learning and modeling efforts compared with PROMODEL. Particular comparisons between the two methodologies are made on (1) resource transit times, (2) activity priorities, (3) resource utilization rates, and (4) basic model structures (i.e. production-line vs. vehicle-loop).

1 INTRODUCTION

Simulation modeling has been implemented by enterprises throughout the world to improve the design and operation of complex systems (Diamond et al. 2002). Commercially available simulation software tools such as PROMODEL have gained popularity and found numerous applications in coping with real-world engineering and management challenges. For instance, Sema and Palaniappa (2000) utilized PROMODEL to assess the impact of bed availability on the waiting time of admitted patients in in-patient flow analysis. Despite their wide acceptance in manufacturing and service industries, these tools have remained little known to construction professionals and rarely applied in modeling and improving construction operations. The research presented is intended to look into the differences between manufacturing and construction systems, and to a certain extent, account for why a direct application of a manufacturing simulation tool in the construction context is deemed improper and difficult. Particularly, PROMODEL, which is a powerful, easy-to-use manufacturing simulation tool for modeling all types of systems and processes (Harrel and Price 2003), was chosen, evaluated and compared against the SDESA, which represents the Simplified Discrete-Event Simulation Approach and its software platform resulting from the recent construction engineering and management research.

The SDESA methodology was proposed and developed with the objective of making simulation of construction operations as easy as applying critical path scheduling (Lu 2003). To make construction simulations more realistic without compromising the simplicity of the original SDESA, SDESA was extended to allow the spatial definition of a construction system in a 3D environment, and to synchronize seamlessly the operations modeling in a dynamic construction system with the 3D construction site layout planning (Lu et al. 2003). And a concurring interruptions model was embedded to accurately simulate effects of operational interruptions upon the system performance (Lu and Chan 2004).

2 SYSTEM CHARACTERISTICS: CONSTRUCTION VS. MANUFACTURING

Ortega and Bisgaard (2000) underscored two main characteristics differentiating construction from manufacturing as: (1) Construction is a project-oriented business that produces unique products; and (2) the product produced by construction is stationary, while the production facilities are mobile. In addition, Table 1 summarizes the general differences between construction and manufacturing operations in the context of systems modeling. Those distinctive characteristics provide the overall background for evaluating, comparing, and applying PROMODEL and SDESA in modeling typical construction systems, as detailed in the following sections.

3 OVERVIEW: PROMODEL VS. SDESA

SDESA is a simplified discrete-event, activity-based modeling system that makes construction simulation as easy as applying the critical path method (CPM) – the current practice for construction planning by construction engineers and managers. On the other hand, PROMODEL is an object-based modeling system featuring an intuitive graphical interface and object-oriented modeling constructs Both eliminate the need for programming in discrete-event. simulation, which can be defined as modeling changes in the state of the system occurring at discrete points in time (Pidd 1992). According to the general classification of simulation strategies (Martinez and Photios 1999), PROMODEL is process interaction (PI) –based; while the modeling strategy behind SDESA confers features of both PI and activity scanning (AS), and is thus termed as the adapted PI (Lu 2005).

The basic modeling elements of SDESA (as listed in Table 2) are designed to be simple and effective for developing a schematic depiction of an operation as dictated by a construction technology (Lu 2003). The modeling elements in PROMODEL (as listed in Table 3) provide a set of constructs for representing the physical and logical components of the system being modeled, and physical elements of the system such as parts, machines, or resources can be referenced either graphically or by name (Harrel 2004).

A PROMODEL model contains objects (locations, entities and resources, and paths) and interactions (arrivals and processing). In contrast, a SDESA model consists of (1) a process flowchart linking flow entities, activities, resources (reusable and disposable) by arrows, (2) a resource pool holding all resource entities involved, and (3) a resource transit information system. To compare the two methodologies, let us consider a simple earth-moving operation example taken from Martinez and Ioannou (1999): at the cut, a pusher and a scraper worked together to push-load soil into the scraper's bowl. The pusher then backtracked to load the next scraper, and the scraper hauled a soil unit (i.e. one scraperful) to the fill, dumped, spread, and then returned to the cut. Once 20 push- loads were completed, the pusher moved toward the side and trimmed the side. After side trimming, the pusher then moved back to continue push-loading scrapers. Each scraper handled a soil unit of 20 m^3. The objective was to find the optimum number of scrapers that equated with one pusher tractor in moving 10,000 m^3 from the cut to the fill.

Table 1: Characteristics of Construction and Manufacturing Systems

Construction Operations	Manufacturing Operations
- More resources are involved in performing an activity. Resource sharing and competition always happen between activities during construction.	- Fewer resources are involved in performing an activity. They are mainly used for product transportation, machine control and product assembly.
- Production facilities are mobile.	- Production facilities are stationary
- More interrelationships between activities and therefore many factors and variables affect the working processes.	- Fewer interrelationships between activities and therefore the working processes are relatively simple.
- Prone to human errors in working process due to being labor-intensive.	- Insignificant human errors in the manufacturing working process because machines are the dominant production resources.
- Buffer is commonly not required in the open-air, outdoor site environment.	- Buffer is always required in the working process to avoid activity disruption.
- The nature of the product/material remains stable and unchanged throughout the whole working process (e.g. concrete).	- The nature of the product/material can change as a result of processing over each work station.
- The working process involves both production-line and vehicle-loop operations.	- The working process involves mainly production-line operations.

Table 2: Modeling Elements Description of SDESA

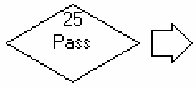
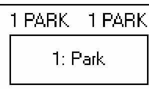
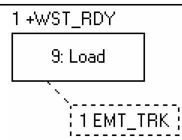
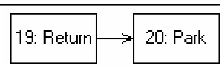
Name	Symbol	Description
Flow Entity		A flow entity diamond heads a series of activities, being the quantity of material units to be handled in a production line or the number of vehicles in a vehicle loop.
Activity		Activity is a task that consumes time and resources in processing a flow entity.
Reusable Resource (RR) Entity		Reusable resources are defined as Resource Entities, limited in availability. They are required to perform an activity, and upon finishing, are released to the resource pool. RR Required are shown in Top Left Corner; RR Released in Top Right Corner.
Disposable Resource (DR) Entity		Disposable resources entities are either intermediate products or command units generated by one activity and required by another; they are used to establish the interdependent relationships between various activities/processes, and can be utilized once only. DR Required of an activity is shown in the Top Left Corner and DR Generated in bottom right corner.
Arrow		Analogous to CPM, arrows link activities by precedence relationships to show the operation logic.
Control Variable(s)	Nil	A control variable can be defined, evaluated and updated in a simulation, e.g. acting as logic condition to control the start of an activity.
Resource Attribute(s)	Nil	Like resource-specific control variables, 3 attributes per resource entity can be specified for representing the properties of resources.

Table 3: Modeling Elements Description of PROMODEL

Elements/Classes	Description
Main Elements	
Entities (or Parts)	Entities are the items processed in the system. Entities of the same type or of different types may be consolidated into a single entity, separated into two or more additional entities or converted to one or more new entity types.
Locations	The places where entities are processed or held. Routing Locations may have a capacity greater than one and may have periodic downtimes as a function of clock time (e.g. shift changes), usage time (e.g. tool wear), usage frequency (e.g. change a dispenser after every n cycles), change of material (e.g. machine setup) or based on some user defined condition.
Resources	Agents used to process and move entities. Resources may be either static or assigned to a path network for dynamic movement.
Path Networks	Aisles and pathways along which entities and resources traverse. Movement along a path network may be defined in terms of distance and speed or by time.
Processing (or routing)	Processes define the routing of entities through the system and what operations take place for each entity at each location. The operation or service times at locations, resource requirements, processing logic, input/output relationship, routing conditions, and move times or requirements can be described.
Arrivals (or production schedule)	Arrivals define the entry of entities into the system such as inter arrival times and quantities.
Shifts (or work schedule)	Shifts define custom work and break schedules.
Additional Elements	
Variables	Variables are used for decision making and statistical reporting.
Attributes	Attributes can be defined for entities and locations

For the earth-moving operations described, Figures 1 and 2 show the SDESA models featuring production-line and vehicle-loop model structures respectively. Note that the production line (Figure 1) traced the life cycle of each material unit (MU– a total of 500 such flow entities) from source to destination, and the four scrapers deployed were treated as reusable resources whose transit times between different activities were specified in the resource transit information system attached to the model; while the vehicle loop (Figure 2) initialized the four scrapers as vehicles (flow entities) to loop through the each-moving cycle, while the 500 material units (MU) were treated as disposable resource entities (SC). Additional transit times of the pusher and scraper resources are given in Table 4.

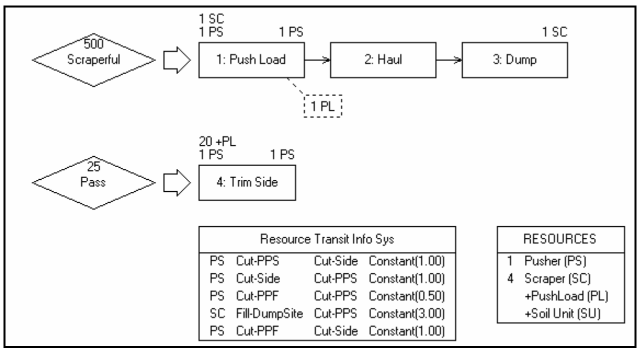


Figure 1: SDESA Simulation Model of Earth-Moving Operation: Production-Lline

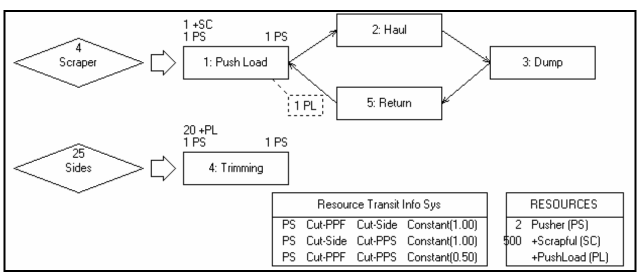


Figure 2: SDESA Simulation Model of Earth-Moving Operation: Vehicle-Loop

In both cases, the logic for trimming side every twenty push loads was simply expressed with a disposable resource "PL" (an information unit denoting one push load completed), which linked the "push load" and "trimming side" activities; and the pusher's transit time delays for working on the two activities at different locations (i.e. push load and trimming side) were specified in the resource transit information system.

Figure 3 shows the counterpart PROMODEL model for the simple scraper and pusher operation with the inter-relationships between locations defined in Processing. The details of the model definition are presented in Table 5 while the transit duration of the resources is specified in the separate spread sheet called the Path Network and the details are shown in Table 6. Referring to Table 5, the entity "Pass_Signal" was used to realize the logic for initiating the Cut Side activity. Combining 20 such "Pass_Signals" produced one Work_Signal, which was required to trigger the Cut Side Activity. A buffer location "Push Ld Signal Arrival" was added in PROMODEL for amassing and converting "Pass_Signals" to Work_Signal. The variables "vPush_Ld" and "vPush_Ld_Signal" kept track of the numbers of Scrapefuls and Pass_Signals arriving at the specific locations respectively.

The above SDESA and PROMODEL models were cross-validated and produced identical outputs in terms of the total project duration of 1314 minutes and the resource utilization rates (less than 0.2% difference). Animations on the two SDESA models and the PROMODEL further revealed the pattern of resources' movement and the sequence of activities, all conforming to the problem statement. Two particular observations were made in comparing the two simulation methodologies based on the earth-moving case study:

<u>Resource Transit Time Delay:</u> In a real construction working environment, the resource transit time from one location to another is uncertain by nature. SDESA can readily simulate this situation by defining the resource transit times as statistical distributions for the traveling and returning trips between two locations independently. In contrast, because the resources' movement in the factory setting of manufacturing mainly involves materialhandling and transportation over a short distance, PROMODEL either does not allow distinguishing the transit time between two locations (under the time mode) or use constant times only to specify the bi-directional transit times respectively (under the distance and speed mode).

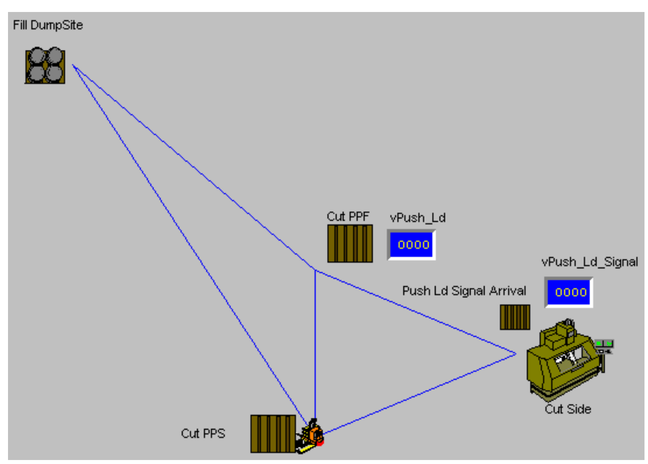


Figure 3: PROMODEL Simulation Model of Earth-Moving Operation

Table 4: Additional Information of Model Activities

Work Package	Start Loc.	Finish Loc.	Duration
(1) Push Load	Cut – PPS	Cut – PPF	Constant (2.00)
(2) Haul	Cut – PPF	Fill – Dump-Site	Constant (4.00)
(3) Dump	Fill – DumpSite	Fill – Dump-Site	Constant (1.00)
(4) Trim Side on One Pass	Cut – Side	Cut – Side	Constant (1.00)

Abbreviations: PPS – Push Point Start;
PPF – Push Point Finish

Activity Priority: Activity priority setting is significant to allocation of limited resources as requested by more than one activity, which is commonplace in construction. For instance, to realize the logic of trimming the side every twenty push loads completed, both PROMODEL and SDESA required assigning higher priority to the "trimming side" activity than to the "push load" activity. Otherwise, the pusher would not engage in the side trimming activity even if the pusher was available after 20 scraperfuls were completed and no scraper was waiting.

To further compare the two simulation methodologies, more complicated concreting and waste handling processes, based on real site operations in the North Part of West Kowloon Reclamation (Site 10) – Phase 1 in Mei Foo, Hong Kong were modeled in the ensuing section

4 CASE STUDY: CONCRETING AND WASTE-HANDLING SIMULATION

142 m^3 concrete was required to pour into the wall and slab steel formwork using a skip and a tower crane over one working day period. 20 truckloads of ready mixed concrete (each 7.2 m^3) were delivered from an off-site concrete plant to the site. It took about 27 minutes to unload one truckload of concrete, which could fill up about 5 skip loads. The tower crane swung up a full skip of 1.5 m^3, poured concrete into the working area and then swung down the empty skip to the truck-unloading area. Laborers then vibrated concrete and leveled off the surface of the pour section. A total of 100 pour sections were placed on that day. In addition, 0.15 m^3 of each truckload of concrete was unloaded by a worker for slump test at the quality control testing station. The concrete waste from testing was collected and transported by the worker to the recycling center on site for making concrete blocks.

The resultant PROMODEL model is shown in Figure 4, with the interrelationships between locations defined in *Processing*. The transit times of resources were defined in the separate spread sheet called Path Network as shown in Table 8 and details of the model development are given in Table 9.

The counterpart SDESA model for the concreting and waste handling operations is an effective combination of production-lines and vehicle-loops for various material handling processes as shown in Figure 5. The additional information of this model is shown in Table 7. In Figure 5, the flow entity "Trucks" arrived on the construction site on an average interval of 25 minutes. The disposable resources, "WST_RDY", "SKP_LD", "EMT_TRK" and "VBT_RDY" served to establish logical connections between different activities/processes. The flow entity "1 Skip" was the vehicle undergoing a "vehicle-loop" process; only 1 skip was available for concreting. Other flow entities went through production-line processes.

In Table 9, the entities "Concrete_Batch" and "Concrete_Waste" represent a truckload of concrete and a unit of concrete waste from testing respectively. The location "Unload_Bay" was a counter for recording the number of Unit_Concrete delivered. The value was automatically deducted by one as one of the units was transported to the location "Pour" for processing. The variable Work in Process "vWIP" increased by 1 once the Unit_Concrete was in processing. When the Unit_Concrete was consumed and one of the sections finished, the variable "vWIP" decreased by 1 and the variable Finished Section "vFinished_Section" increased by 1.

The waiting duration "WAIT T(4,5,6) of the Entity "Concrete_Waste" was the sum of the time spent on the test "T(2.5,3,3.5)" and the waste collection "T(1.5,2,2.5)", corresponding to Activity 2 "Test" and Activity 12 "Collect Test Waste" in the SDESA model.

The transit and return times of the resources were identical and all the travel time between Locations was set in bi-directional mode. The location "Unload_Bay" was needed in PROMODEL, acting as a buffer location so as to avoid disruptions on the concrete unloading activity.

The SDESA and PROMODEL models were executed for 10 Monte Carlo duplications. The simulation started at time zero and the time units in the model definitions were on minute basis. The results indicated the average pour duration of 507 minutes for SDESA and of 524 minutes for PROMODEL. The 17 minutes (3.4%) difference can be accounted for by minor differences in model definitions and random variations in statistical sampling. Animations on both models further revealed the valid pattern of resources' movement and the correct sequence of activities, all conforming to the actual observations. Two additional observations were made in comparing the two simulation methodologies based on the concreting case study:

Resource Utilization Rate: The simulation results on resource utilization rates for the SDESA and PROMODEL models are given in Table 10. In PROMODEL, the resource states can be classified in five categories: (1) % In Use (the percentage of time the resource spent transporting or processing an entity, or servicing a location or other resources.); (2) % Travel to Use (the percentage of time the

Table 5: Processing Information of PROMODEL Model

Entity	Location	Operation	Output	Destination	Move Logic
Scrapeful	Cut_PPS	Get PS Get SC	Scrapeful	Cut_PPF	Inc vPL, 1 Move with PS Then free
Scrapeful	Cut_PPF		Scrapeful	Fill_DSite	Move with SC
			Pass_Signal	PL_S_Arr.	Inc vPL_S, 1
Scrapeful	Fill_DSite	Wait 1 min Free SC	Scrapeful	Exit	
Pass_Signal	PL_S_Arr.	Combine 20 as Work_Signal	Work_Signal	PL_S_Arr.	
Work_Signal	PL_S_Arr.		Work_Signal	Cut_Side	
Work_Signal	Cut_Side	Get PS, 2 Wait 1 min Free PS Dec vPL_S, 20	Work_Signal	Exit	

Resource : PS (Pusher), SC (Scraper)
Location : Fill_DSite (Fill_DumpSite), PL_S_Arr. (Push_Ld_Signal_Arrival),
Variable : PL (Push_Ld), PL_S (Push_Ld_Signal), INC (Increase), DEC (Decrease)

Table 6: Resource Transit Times for PROMODEL Model

			Input			Output
Resource	**From**	**To**	**Directional**	**Distance (m)**	**Speed (m/min)**	**Time (mins)**
Pusher	Cut-PPS	Cut-PPF	Bidirectional	100	50 (F)	2
	Cut-PPF	Cut-PPS	Bidirectional	100	200 (E)	0.5
	Cut-PPS	Cut-Side	Bidirectional	200	200 (E)	1
	Cut-PPF	Cut-Side	Bidirectional	200	200 (E)	1
Scraper	Cut-PPS	Cut-PPF	Bidirectional	100	50 (F)	2
	Cut-PPF	Fill_DSite	Unidirectional	200	50 (F)	4
	Fill_DSite	Cut-PPS	Unidirectional	450	150 (E)	3

F is the full traveling speed of resources
E is the empty traveling speed of resources

Table 7: Additional Information of Model Activities

Work Package	Start Loc.	Finish Loc.	Duration, Tri (min, mode, max)
(1) Enter Site & Move to Testing Station	Site Entry/Exit	Test Station	3, 3.5, 4
(2) Quality Control Test	Test Station	Test Station	2.5, 3, 3.5
(3) Park to Unload	Test Station	Unload Bay	3, 3.5, 4
(4) Go to Wash	Unload Bay	Washing Bay	0.3, 0.5, 0.7
(5) Wash & Leave	Washing Bay	Site Entry/Exit	0.6, 1, 1.4
(6) Load	Unload Bay	Unload Bay	0.7, 1, 1.3
(7) Hook Up	Unload Bay	Working Level	1, 1.2, 1.4
(8) Pour	Working Level	Working Level	0.4, 0.5, 0.6
(9) Hook Down	Working Level	Unload Bay	1, 1.2, 1.4
(10) Vibrate	Working Level	Working Level	0.8, 1, 1.2
(11) Level Off	Working Level	Working Level	1.8, 2, 1.9
(12) Collect Test Waste	Test Station	Test Station	1.5, 2, 2.5
(13) Transport	Test Station	Recycle area	2.5, 3, 3.5
(14) Unload to Formwork	Recycle area	Recycle area	1.5, 2, 2.5
(15) Vibrating & Level Off	Recycle area	Recycle area	2, 2.5, 3

resource spent traveling to a location or transporting, processing, or servicing an entity, location, or resource. This also includes pickup and deposit time.); (3) % Travel to Park (The percentage of time the resource spent traveling to a path node to park.); (4) % Idle (The percentage of time the resource was available but not in use.); and (5) % Down (The percentage of time the resource was unavailable due to unscheduled downtimes.). The resource states in SDESA are divided into 2 categories only, i.e. being productive / busy or being non-productive / idle, the transit time is regarded as part of productive state, and the utilization rate of the resources is the productive time of the resource (excluding idle) divided by the sum of the productive time and the idle time of the resource.

To facilitate comparison with SDESA, the utilization rates under PROMODEL in Table 10 are the sum of categories (1), (2) and (3). It is noted that the results for two models were statistically the same (less than 5 % difference) except for the resource of General Laborer Ground, whose utilization rate was much higher in PROMODEL than in SDESA (63% vs. 20%) because PROMODEL recognized the time spent on waiting for the availability of the crane as part of the working time. The entity "Unit_concrete" was available nearly all the time at the location "Unload Bay", and therefore, the laborer was engaged in an active state by the entity in waiting for the availability of the crane. In SDESA, this waiting time was treated as idle time, and as a result, the utilization rate of this resource was much lower than decided by PROMODEL. It is clearly seen that construction and manufacturing operations have distinctive perceptions of resource utilization due to differences in respective working practices and environments.

Production-line vs. Vehicle-loop: In SDESA, a working process can be portrayed as a production-line or a vehicle-loop. This provides the flexibility to model the repetitive and cyclic processes in a construction system. However, the vehicle-loop definition (as the skip flow in Figure4) is not commonly encountered in manufacturing operations and hence is not allowed in PROMODEL. This presents one major limitation for applying PROMODEL to construction.

Table 8: Resource Transit Time [Tri (min, mode, max)] in PROMODEL Model (Bidirectional)

Resource	From	To	Duration,
CRANE	Unload Bay	Work Area	T(1, 1.2, 1.4)
WST_LB	Test Station	Recycle Center	T(2.5, 3, 3.5)

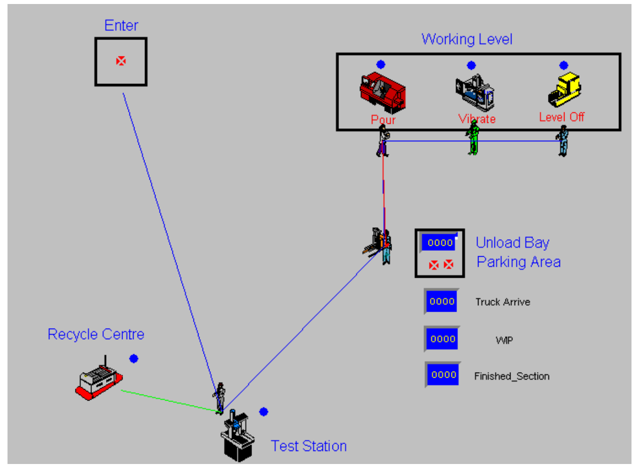


Figure 4. PROMODEL Model for Concreting and Waste-handling Processes

5 CONCLUSION

The present research has looked into the differences between manufacturing and construction systems, and to a certain extent, account for why a direct application of a manufacturing simulation tool in the construction context is deemed improper and difficult. Particularly, PROMODEL was chosen, evaluated and compared against SDESA by using a simple earth-moving operation and a real site operation as case studies. We demonstrated that SDESA can adequately, precisely depict the construction operations with much less learning and modeling efforts as compared with PROMODEL. Our experiences with training engineering students without any simulation background showed to learn and apply SDESA required roughly one third of the time as needed for PROMODEL in handling the identical definition of a construction problem.

ACKNOWLEDGMENTS

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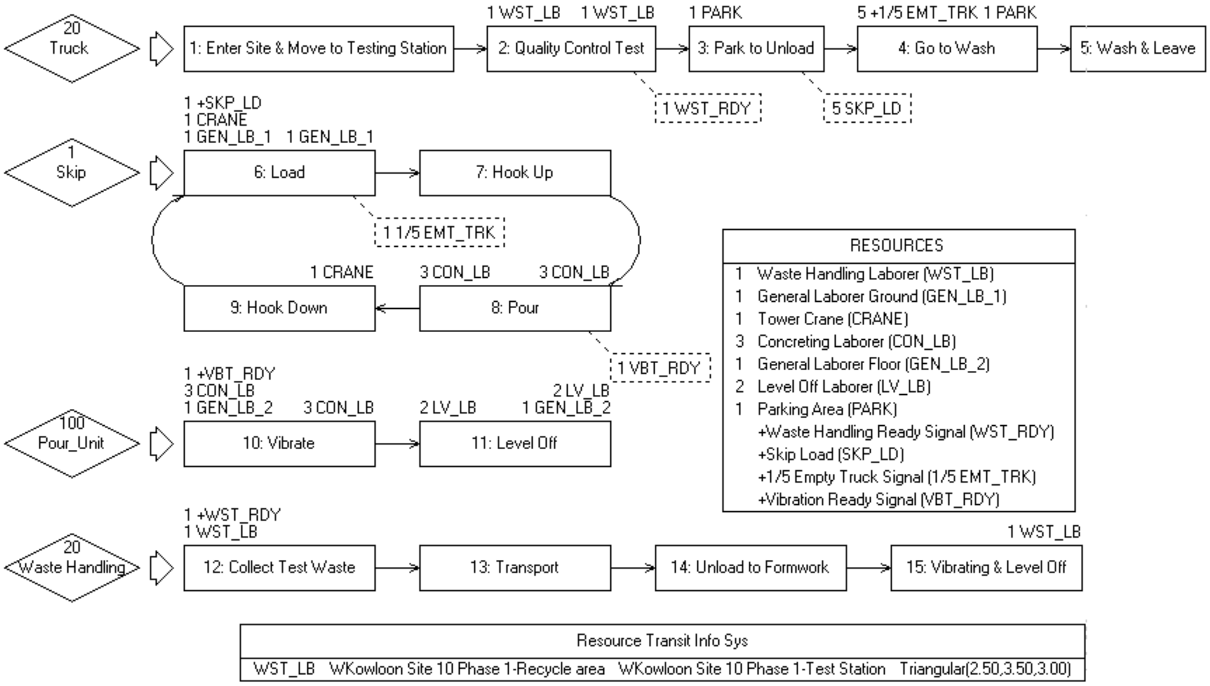

Figure 5: SDESA Simulation Model for Waste Handling Process

Table 9: Processing Information of PROMODEL Model

Entity	Loc.	Operation	Output	Dest.	Move Logic
Conc_Batch	Enter		Con_Batch	Test_Station	
Con_Batch	Test_Station	Wait T(2.5, 3, 3.5)	Con_Batch	Parking_Area	Inc vTrk_Arr, 1
Con_Batch	Parking_Area	Split 5 AS Unit_Con			
Unit_Con	Parking_Area		Unit_Con	Unload_Bay	
Unit_Con	Unload_Bay	Get GEN_LB_1 Get CRANE Wait T(0.7, 1, 1.3) Free GEN_LB_1	Unit_Con	Pour	Move with CRANE Inc vWIP, 1
Unit_Con	Pour	Get 3 CON_LB Wait T(0.4, 0.5, 0.6) Free CRANE	Unit_Con	Vibrate	
Unit_Con	Vibrate	Get GEN_LB_2 Wait T(0.8, 1, 1.2) Free 3 CON_LB	Unit_Con	Level_Off	
Unit_Con	Level_Off	Get 2 LV_LB Wait T(1.8, 1.9, 2) Free 2 LV_LB Free GEN_LB_2	Unit_Con	Exit	Inc vFin_Sect, 1 Dec vWIP, 1
Con_Wst	Enter		Con_Wst	Test_Station	
Con_Wst	Test_Station	Get WST_LB Wait T(4, 5, 6)	Con_Wst	Recycle_Cen	Move with WST_LB
Con_Wst	Recycle_Cen	Wait T(3.5, 4.5, 5.5) Free WST_LB	Con_Wst	Exit	

Abbreviations:

Entity : Unit_Con (Unit_Concrete), Con_Wst (Concrete_Waste), Con_Batch (Concrete_Batch)
Location : Recycle_Cen (Recycle_Center)
Variable : Fin_Sect (Finished Section), Trk_Arr. (Truck Arrival), WIP (Work In Process)

Table 10. Resource Utilization Rate Comparison

Resources Entity	SDESA	PRO MODEL
General Laborer Ground (GEN_LB_1)	19.90	63.42
Concreting Laborer (CON_LB)	29.74	28.57
General Laborer Floor (GEN_LB_2)	57.26	55.33
Level Off Laborer (LV_LB)	37.51	36.29
Waste Handling Laborer (WST _LB)	62.92	59.07
Tower Crane (CRANE)	77.41	74.54

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