Application Framework for Mapping and Simulation of Waste Handling Processes in Construction

Ming Lu, M.ASCE[1]; Chi-Sun Poon[2]; and Lap-Chi Wong[3]

Abstract: This research is focused on modeling waste-handling processes in construction, with particular emphasis on how to map out and simulate on-site waste sorting processes. The research proposes an application framework for (1) guiding the development of process mapping models and simulation models; and (2) further assessing the cost effectiveness of on-site waste sorting efforts under practical site constraints (such as labor resource availability, time control on refuse chute usage, and limited working area space in a building site). The connection has been established between the mapping and simulation techniques in the context of modeling waste handling processes in construction sites, such that the process flowchart resulting from the mapping technique can serve as convenient model input to facilitate the creation of a "dynamic" operations simulation model. A case study of the on-site waste sorting method with one refuse chute for waste classification is presented to demonstrate the complete application framework spanning (1) process mapping; (2) mapping-to-simulation model conversion; and (3) method optimization based on valid simulations.

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Introduction

Construction and demolition (C&D) wastes result from the construction, renovation, and demolition of structures including buildings of all types (both residential and nonresidential), road repaving projects, bridge repair, and the cleanup associated with natural and human-made disasters (Tchobanoglous and Kreith 2002). How to dispose of C&D wastes in a cost-effective, environmentally friendly fashion presents one of the major environmental challenges for many municipalities around the world (Faniran and Caban 1998). According to past records, C&D materials contributed to 44% of the municipal solid waste disposed of at the landfill sites in Hong Kong (Hong Kong EPD 2000), standing on the high end as compared with 42.2% of total solid waste in England and Wales (Lawson and Douglas 2001), 15–30% in Kuwait (Kartam et al. 2004), 15–20% in Taiwan (Taiwan EPA 1999), 23% in the United States (Apotheker 1990), and the worldwide average of 13–29% (Bossink and Brouwers 1996). The increasing amounts of C&D wastes cause rapid depletion of landfill space available and bring about an increasing demand for natural aggregates, thereby inflicting ecological and environmental damages on the earth (Hsiao et al. 2002). Thus, how to reduce the generation of C&D wastes and how to ease the impact of C&D wastes generated on the ecosystem are recognized as critical social issues on the global scale. Many governments have recently launched initiatives to effectively address the problems posed by landfilling C&D wastes through source reduction, reuse, and recycling (Tchobanoglous and Kreith 2002). For instance, to reduce the construction related waste, the United Kingdom introduced a landfill tax scheme that resulted in a marked increase in the number of fixed and mobile crushing and recycling sites (Lawson and Douglas 2001). In the United States, Canada, and Europe, large-scale C&D waste processing plants emerged to manage waste streams ranging from 500–1,500 tons/day (Perez 1994). In Hong Kong, government specifications promote the use of paving blocks made with 70–100% recycled concrete aggregates in order to facilitate the recycling of C&D wastes (Poon and Chan 2006).

Researchers have also developed both mathematical and descriptive models in an attempt to assess the problems associated with C&D wastes. To estimate and predict the future trend of concrete waste generation in Taiwan, Hsiao et al. (2002) developed a dynamic model and employed statistical analyses to predict the target rate and the net economic benefit for recycling so as to avoid overloading existing and projected landfill capacities. Huang et al. (2002) reported a feasibility study of using a mechanical sorting process that segregated C&D wastes into different streams of products for recycling. In contrast with the estimation of the net economic benefit for recycling C&D wastes, Stenis (2005) utilized industrial management models to estimate the true internal costs of construction waste classification in Sweden. The Stenis study set forth a principle for estimating the shadow price costs and revenues of a waste-related industrial company, which constituted the basis for estimation of the "full" company cost and estimation of the "true" company business fi-

[1]Assistant Professor of Construction Engineering and Management, Dept. of Civil and Structural Engineering, Hong Kong Polytechnic Univ., Hung Hom, Kowloon, Hong Kong, China. E-mail: cemlu@polyu.edu.hk

[2]Professor of Environmental Engineering, Dept. of Civil and Structural Engineering, Hong Kong Polytechnic Univ., Hung Hom, Kowloon, Hong Kong, China. E-mail: cecspoon@polyu.edu.hk

[3]Research Assistant, Dept. of Civil and Structural Engineering, Hong Kong Polytechnic Univ., Hung Hom, Kowloon, Hong Kong, China.

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nancial result in a waste management context. Shen et al. (2004) proposed a process-description approach—called the waste management mapping model—to assist the planning of waste management procedures in Hong Kong's construction sites. Although the mapping model provided a systematic way for describing the general waste management processes, it failed to show the matching, queuing, and transit of various resources and the intricate interdependencies between different processes. Applications of information technologies have also been proposed to control and reduce C&D wastes and to increase the efficiency of on-site waste management, such as the use of bar-coding systems (Li and Chen 2003; Li et al. 2005) and the integration of the global position system, geographical information systems, and the wide area network (Li et al. 2005). Despite their potential for alleviating the difficulty in tracing the exact amounts and locations for waste generation in construction sites, those technologies are yet mature for capturing sufficient site data that support analytical modeling of dynamic resource interactions and complex interprocess interactions in handling C&D wastes.

In general, C&D wastes can be classified into inert and noninert materials (Hong Kong EPD 2000). Inert wastes are nonorganic materials that can be recycled (such as steel) or are suitable for land reclamation and site formation (such as rubble, earth, and concrete). Bamboo, timber, vegetation, packaging waste, and other organic materials are classified as noninert wastes and are mainly disposed of at landfills. A practical constraint that renders C&D waste handling and recycling activities difficult—in both technical and economical senses—lies in the fact that inert waste materials generated from construction are often blended with other noninert components (Lawson and Douglas 2001). Such contaminated waste materials would require costly off-site treatment for segregating the reusable inert portion. In Hong Kong, C&D wastes are largely deemed economically infeasible for recycling or reuse in reclamation and site formation works, and instead, are disposed of in landfills (Poon et al. 2004).

An investigation of building projects in Hong Kong by Poon et al. (2001) identified the practical need to develop mapping and modeling tools that describe and analyze waste handling methods and work flows in construction, encompassing the processes of sorting, segregating, labeling, storing, protecting, and disposing of waste materials of various types in a building site. Moreover, an on-site waste sorting method using a refuse chute was proposed for waste classification and segregation in an attempt to facilitate the recycling and reuse of C&D wastes (Poon et al. 2001).

This research is focused on modeling waste-handling processes in construction, with particular emphasis on mapping and simulation of on-site waste sorting processes. Instead of trying to directly reduce the amount of construction wastes generated at the source, the research is intended to assess the cost effectiveness of on-site waste sorting efforts under practical site constraints (such as labor resource availability, time control on refuse chute usage, and limited working area space in a building site). We herein propose an application framework to guide the mapping and simulation of waste-handling processes as follows: First, we enhance the waste management mapping model (Shen et al. 2004) into a process mapping technique that can represent the intricate logical or technological constraints and complex interdependent relationships between components of a typical waste-handling system in construction. Application of the process mapping technique results in a flowchart depicting detailed waste-handling procedures, which not only helps visualize the method statement in a structured, standardized format, but also serves as convenient model input to generate a "dynamic" operations simulation model by the simplified discrete-event simulation approach (SDESA) (Lu 2003; Lu and Wong 2006). With the simulation model, we can readily evaluate, analyze, and optimize the efficiency and cost effectiveness of a given waste-handling method being postulated through straightforward simulation experiments.

The remainder of the paper starts with introducing the waste management mapping model and the SDESA simulation model, followed by establishment of the connection between the two techniques in the context of modeling waste handling processes in construction sites. A case study of the on-site waste sorting method with one refuse chute for waste classification—characteristic of the practical waste handling processes in building sites—is presented to demonstrate the complete application framework beginning from process mapping, to mapping-to-simulation-model conversion, through to method optimization based on valid simulations. The problem statement for the case study is first given in the following section. The case study for waste handling is based on experiences and conditions on a typical building site in Hong Kong. The limited space in the congested working area imposes available space as a major constraint in the design of the waste management option, which aims at attaining both productivity and safety.

Problem Statement

After the formworking and rebar fixing activities on slabs and beams on a building floor had been completed, a number of timber laborers from the carpenter crew and a number of steel laborers from the rebar crew were responsible for collecting and disposing of noninert waste (timber waste) and inert waste (steel waste), respectively, within 1 h and 40 min (100 min)—before handing over the working area to the concreting crew. Note, for ease of representation, in the problem statement and ensuing mapping/simulation models, the labels of "timber waste" and "steel waste" serve to denote general "noninert waste" and "inert waste" classifications of C&D wastes; as such, steel laborers handled steel waste while timber waste was dealt with by timber laborers.

One refuse chute was installed on the working floor to facilitate the on-site sorting of timber and steel wastes. Timber waste was gathered on the working floor and transferred via the refuse chute into a "timber" skip container located on the ground, while steel waste was temporarily collected into several piles (storage blocks) near the refuse chute on the floor. According to site regulations, the refuse chute was exclusively used for processing timber waste in the first hour, and then would switch to handle the steel waste in the second hour. As the second hour began, a "steel" skip container would substitute the one for timber waste on the ground to receive steel waste. In the case study, it was estimated that 16 units of timber waste and 12 units of steel waste were scattered on the floor. Note one unit of waste was about one wheelbarrow load that could be handled by a laborer at a time. Each temporary storage block (pile) roughly accommodated one unit of steel waste, and it was not allowed to stack up more than one waste unit in one pile. In addition, four units of timber waste would be required to fully load the timber skip container while six units of steel waste would fill up the steel one. Once the skip containers were full, pickup trucks would be called in to transport the timber and steel wastes to a landfill and a recycling facility, respectively. The objective of the case study is to decide on the optimum combination for resource provisions with regard to (1)

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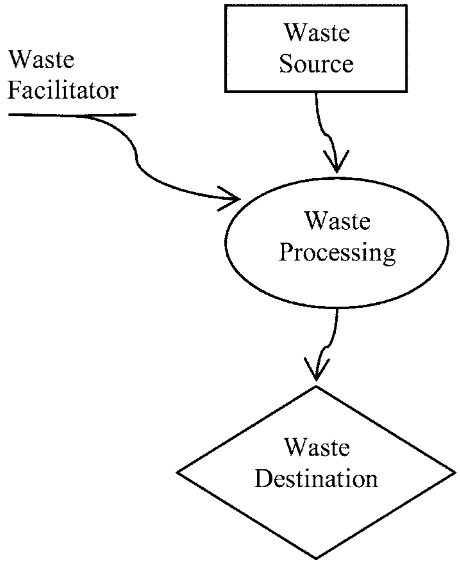

Fig. 1. Basic modeling elements for waste management mapping model

the number of timber laborers; (2) the number of steel laborers; and (3) the number of storage blocks to be designated on the building floor, so as to materialize cost-effective waste handling management subject to constraints such as the time control in refuse chute usage (the first hour designated to timber waste) and the total processing time window (100 min).

Process Mapping Model

Through linking four basic modeling elements, the waste management mapping model proposed by Shen et al. (2004) provides a simple, straightforward mapping technique for depicting waste-handling processes in construction. The waste source (rectangle shape in Fig. 1) denotes waste generation or the location where wastes originate. The waste processing (ellipse shape in Fig. 1) denotes various waste-handling activities like loading waste and sorting waste. The waste facilitator (symbols tagged to waste processing in Fig. 1) denotes the resource or tool used to facilitate a waste-handling activity, including laborers, tools, and mechanical plants. The waste destination (diamond shape as in Fig. 1) denotes the final status in waste handling (such as reuse or recycle), or the final place that wastes are delivered to (such as landfills or reclamation sites). A simple waste flow mapping is a connection of the four elemental symbols by arrows representing precedence relationships according to the operation logic. The mapping model for the case study problem is shown in Fig. 2, consisting of four waste-handling processes as for (1) timber waste; (2) steel waste; (3) timber waste pickup trucks; and (4) steel waste collection vehicles.

In developing the process mapping model, two enhancements are made for the original mapping technique so as to clearly represent (1) the state changes over the site space of wastes and facilitating resources; and (2) interdependent relationships between concurring processes. The first enhancement entails discretizing the space of a site system into key locations where processing activities occur, and the start and finish locations of each activity are further linked to the processing activity (ellipse). For example, two identical location tags of "working platform" are attached to the top right of the ellipse representing the processing activity "collect timber waste," indicating timber waste collection is confined to the working platform on the building floor. For the processing activity "transport timber waste," the location tags attached are "working platform" and "chute location," meaning the timber waste traverses from the work platform to the opening of the refuse chute on the floor. The second enhancement requires the use of dotted arrows to portray interprocess dependencies. For example, a dotted arrow linking the processing "dump timber waste" and the processing "load stored steel waste" indicates that the timing control logic on the refuse chute—1 h after the start, the timber laborers should have finished handling all timber waste, and the steel laborers began loading steel waste from the storage blocks (piles) into barrows, and then into the refuse chute. A second example is the dotted arrow connecting the processing "dump timber waste" to the source "refuse truck," representing that the completion of handling four units of timber waste produces one truckload ready for follow up "load timber truck" processing.

Note, it has been reasonably assumed that for typical waste handling activities in building sites, the amounts of wastes to be handled can be measured and the resource and time requirements for handling each processing activity can be estimated. In fact, the similar quantity–takeoff analysis techniques can be applied as in the standard estimating practice in deciding the amount of waste of certain type by a particular unit of measure for a particular process. In our case study, the quantities of timber and steel waste units are marked in the waste sources as 16 and 12, respectively; the resource requirements by each processing activity are annotated to the top left of a processing ellipse (Fig. 2).

In short, the process mapping model shown in Fig. 2 not only helps visualize the waste-handling method statement in a clear, structured, and standardized format, but also serves as convenient model input to generate a "dynamic" operations simulation model by the SDESA, which is discussed next.

Process Simulation Model

Pidd (1992) defined discrete-event simulation as modeling changes in the state of the system occurring at discrete points in time. SDESA was originally proposed as a simplified discrete-event, activity-based modeling method intended to make construction simulation as easy as applying the critical path method—which is the current practice for construction planning by construction engineers and managers (Lu 2003). To make construction simulations more realistic without compromising the simplicity of the original SDESA, SDESA was extended to (1) allow the spatial definition of a construction system in a three-dimensional (3D) environment; and to (2) seamlessly synchronize the operations modeling in a dynamic construction system with a 3D construction site layout plan (Lu et al. 2003). An interruptions model was further embedded to accurately simulate the effects of concurrent operational interruptions upon system performances (Lu and Chan 2004).

Simulation methodologies based on *activity cycle diagrams* and the *activity scanning* modeling paradigm (such as CYCLONE, STROBOSCOPE) have been thoroughly researched and well established for modeling construction operations; in contrast, popular commercial simulation software systems (including PROMODEL, ARENA, EXTEND, QUEST, SLAM, ENTERPRISE DYNAMICS, PROCESS V3) are deeply rooted in manufacturing and mostly run on the process interaction model-

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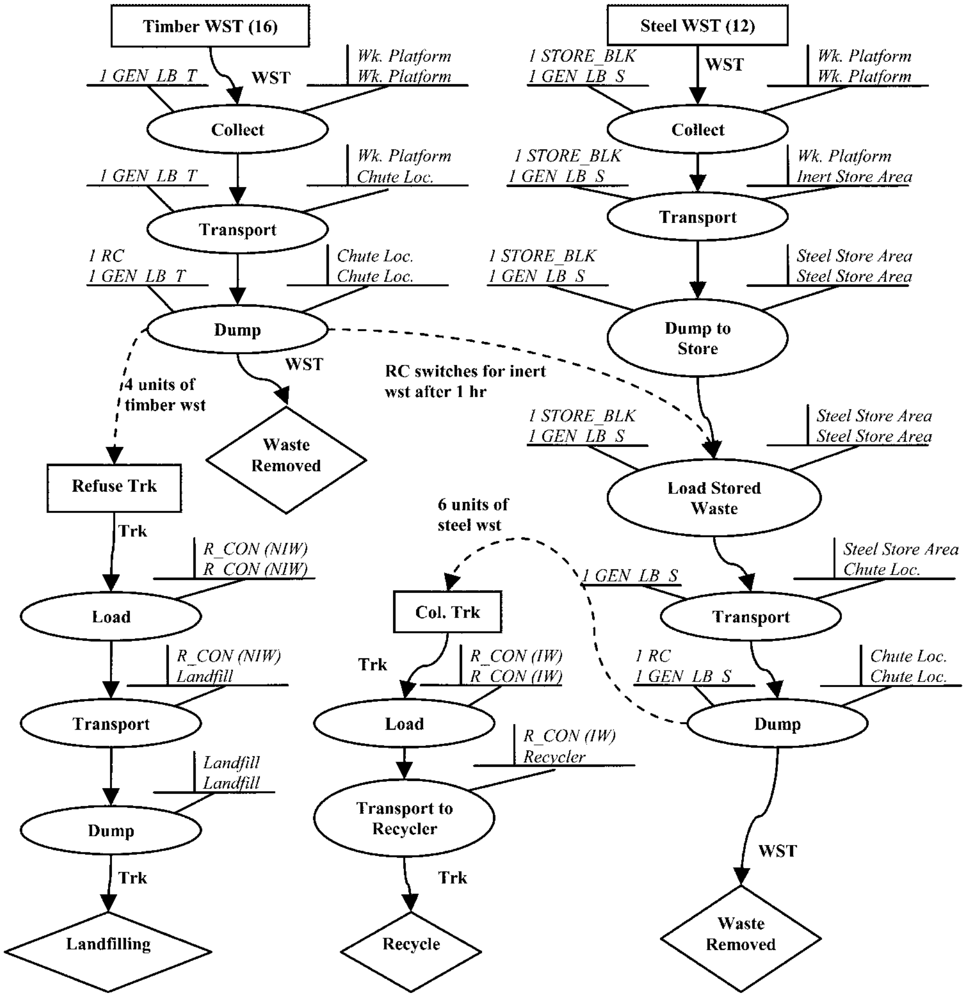

Abbreviations:

Resource	:	GEN_LB_T (General Laborer (Timber)), GEN_LB_S (General Laborer (Steel)), STORE_BLK (Storage Block), RC (Refuse Chute),
Flow entity	:	Timber WST (Non-inert Timber Waste), Steel WST (Inert Steel Waste), Refuse Trk. (Non-inert/Timber Waste Truck), Col. Trk (Inert/Steel Waste Collection Truck)
Location	:	Wk. Platform (Working Platform), Chute Loc. (Chute Location), R_CON (NIW) (Refuse Container for non-inert waste), R_CON (IW) (Refuse Container for inert waste)

Fig. 2. Process mapping model for the waste management processes in the case study problem. Resource: GEN_LB_T=general laborer (timber); GEN_LB_S=general laborer (steel); STORE_BLK=storage block; and RC=refuse chute. Flow entity: Timber WST=noninert timber waste; steel WST=inert steel waste; refuse Trk=noninert/timber waste truck; and Col. Trk=inert/steel waste collection truck. Location: Wk. platform=working platform; Chute Loc.=chute location; R_CON(NIW)=refuse container for noninert waste; and R_CON(IW)=refuse container for inert waste.

ing strategy (Martinez and Ioannou 1999). The modeling strategy behind SDESA confers features of both the process interaction strategy and the activity scanning strategy, and is thus classified as the *adapted* process interaction (Lu 2005). Lu (2005) presented an in-depth comparison of different modeling paradigms, as illustrated with a classic construction example of earthmoving with scrapers. To facilitate the practice improvement by use of simulation tools in construction, Lu and Wong (2006) generalized the main characteristics that differentiate a construction system from a manufacturing system with respect of applying simulation modeling. Moreover, the SDESA methodology was compared with PROMODEL—which is influential and popular in manufacturing—and validated by applying PROMODEL alongside SDESA to typical construction systems; SDESA is found to be more flexible and straightforward in coping with construction systems (Lu and Wong 2006). Hence, in the present research, SDESA is selected as the simulation method and the in-house software of SDESA is utilized as the computer tool to facilitate the design and execution of simulation experiments. The basic modeling elements of SDESA are shown in Table 1, which are designed to be simple and effective for developing a schematic depiction of an operation by a given construction technology. Note, SDESA distinguishes *disposable resources* from other material handling resources and facilitating resources (e.g. vehicles, machinery, manpower, and space blocks). In contrast, disposable resources can be utilized for once only and are either material units or information units, which are generated as intermediate products by some activities and requested by others during simulation. In such a way, SDESA establishes the interdependency relationships between activities or processes.

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Table 1. Modeling elements description of SDESA

Name	Symbol	Description
Flow Entity	20 Concrete Ld	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	14: Transport	Activity is a task that consumes time and resources in processing a flow entity.
Reusable Resource (RR) Entity	1 PARK 1 PARK 3: Park	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	1 +WST_RDY 2: Load 1 EMT_TRK	Disposable resources entities are either intermediate products or command units generated by one activity and required by another; they are used 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	16: Return → 17: Park	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.

In a construction system, *moving entities* of various types undergo interactive, dynamic processes that are interdependent and interconnected under resource availability constraints and technology constraints. Analogous to the treatment of parts (or raw materials) as moving entities along a production line in a manufacturing setting, a moving entity in typical repetitive/cyclic construction operations can be identified as a *material unit* being handled, which flows through a construction process consisting of a sequence of activities and interacts with construction resources in those activities. In modeling waste-handling processes, the basic mapping model structure can be readily converted into a SDESA simulation model following the production-line modeling philosophy, which traces the life cycle of moving entities from source to destination in the system (Fig. 3). Note, SDESA designates a diamond block for initializing the waste units to be handled and a rectangle block for representing a processing activity. For one activity, the resources required to perform the activity are shown in the top-left corner of the activity block, with resources released upon finishing the activity marked in the top-right corner. What really distinguishes construction from manufacturing is the working patterns of resources involved in construction (Lu 2005). In contrast with manufacturing, resources in construction are commonly not fixed at one location on one activity; rather, they move back and forth to serve multiple activities and facilitate handling moving entities of different types in a construction system. In order to provide the flexibility to model time delays in connection with the facilitating resources' transit between various locations on site, a *resource transit information system* is attached to a SDESA model. In addition, SDESA also defines the start and end locations for each activity as activity attributes, which are linked to a model's definition of *location set* consisting of key locations of the site system. Illustrated with our

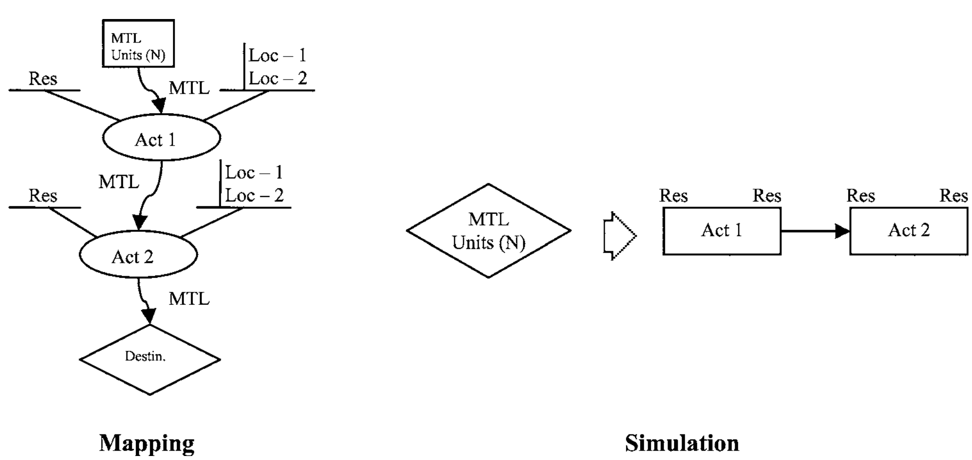

Fig. 3. Basic model structure conversions from mapping model to SDESA simulation model

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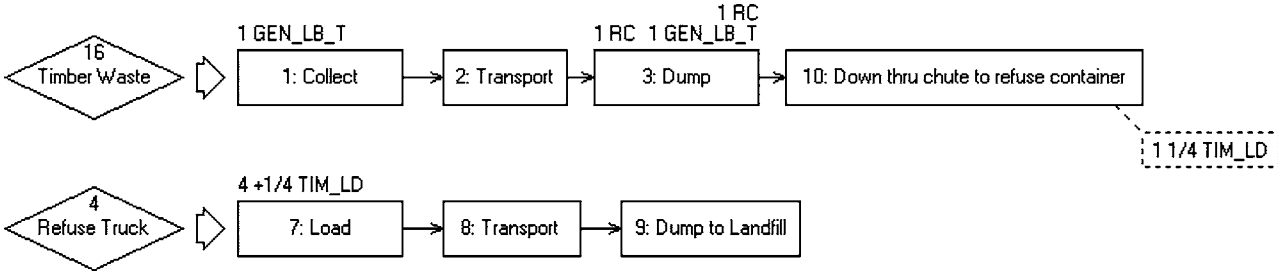

Fig. 4. SDESA submodel for noninert (timber) waste handling in case study

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case study, the SDESA terminologies and modeling methodology are explained in detail as follows.

Fig. 4 shows part of the converted SDESA model for handling 16 units of timber waste on the building floor and four truckloads of timber waste collected on the ground. In Fig. 4, one timber laborer (1 Gen_LB_T) is requested at activity "1: Collect," and released at the end of activity "3: Dump." Note activity "3: Dump" also requires the availability of the refuse chute (RC) resource. To link the two parallel processes in timber waste handling, "1 1/4 TIM_LD"—a disposable resource entity—is generated as a result of finishing activity "10: Down thru chute to refuse container," representing the generation of the amount of waste equivalent to a quarter of the volume capacity of a pickup truck. Note, four such resource entities available would be the prerequisite to initiate activity "7: Load" (i.e., the amount of timber waste generated is sufficient to start loading a refuse truck). Fig. 5. exhibits part of the SDESA model for handling 12 steel waste units and two truckloads of steel waste. A steel laborer (1 GEN_LB_S) together with a vacant temporary storage block (1 STORE_BLK) should be available in order to commence handling one steel waste unit at activity "4: Collect." Following activity "5: Transport," the waste unit is moved to the storage block, producing a disposable resource entity (1 ST_WST_RDY), which represents one steel waste unit is in store and ready for follow up handling. Note the ensuing activity "14: Load stored steel waste" is contingent on satisfying three conditions simultaneously: (1) one steel waste unit is in store; (2) one steel laborer is available; and (3) the refuse chute is designated to processing steel waste. The first two conditions are expressed in terms of availability of limited resource entities (i.e., disposable "1 ST_WST_RDY" and nondisposable "1 GEN_LB_S"). Enforcing the third condition requires the definition of a *control variable* in the SDESA model called the "refuse chute switch," whose value is set as either 0 (refuse chute for timber waste) or 1 (refuse chute for steel waste). According to the timing constraint for refuse chute usage, the control variable is initialized as 0 at the beginning of simulation and only switched to 1 at the end of the 60th min. Thus, meeting the third condition is to ensure "refuse chute switch" being equal to 1. The storage block (1 STORE_BLK)—treated as a nondisposable resource entity—is freed at the end of activity "14: Load stored steel waste." Similar to timber waste handling, after being moved by the laborer from the temporary storage block to the refuse chute (i.e., activity "15: Transport"), the steel waste unit is transferred via the refuse chute into the ground refuse container holding steel. Consequently, "1 1/6 STL_LD" (a disposable resource entity representing the generation of the amount of waste equivalent to one sixth of the volume capacity of a steel collection vehicle) is generated at the end of activity "17. Down thru chute to refuse container," which serves to link the two parallel processes shown in Fig. 5. Note, six such disposable resource entities would be the prerequisite to initiate the activity "11: Load" (i.e., the amount of steel waste generated is sufficient to start loading a steel collection vehicle).

The complete computer model for the case study (combining Figs. 4 and 5) was built on the Windows-based SDESA simulation platform developed in house. Fig. 6 shows a snapshot of the

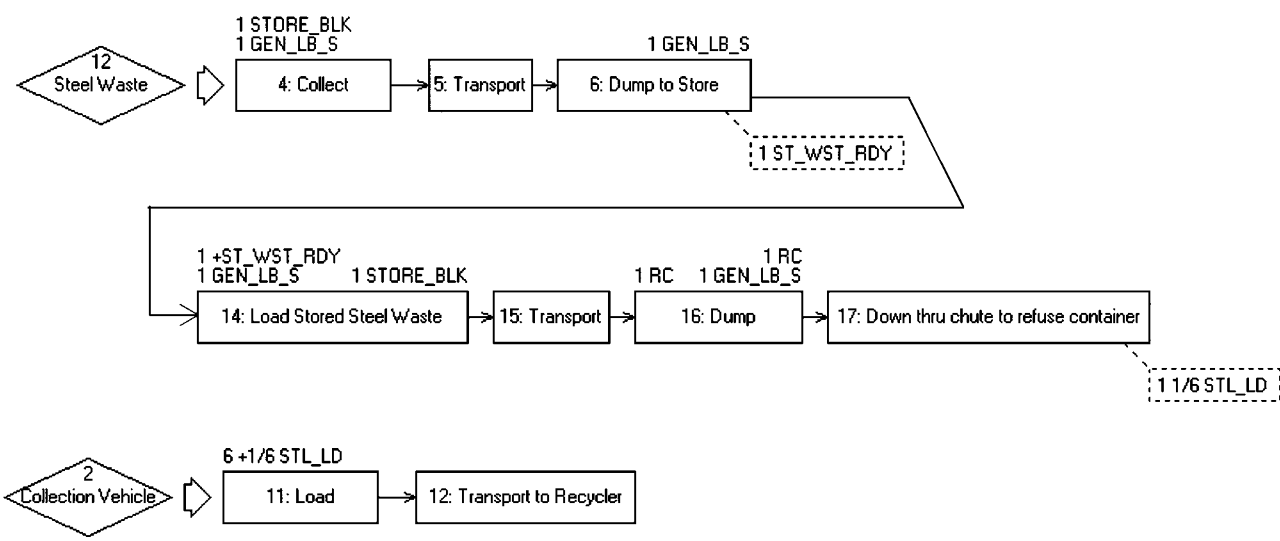

Fig. 5. SDESA submodel for inert (steel) waste handling in case study

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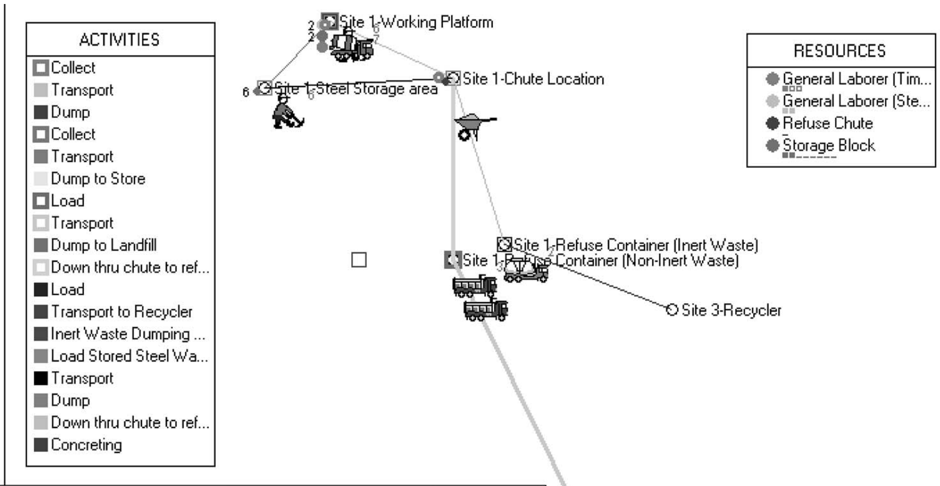

Site	Location	X	Y	Z
Site 1	Working Platform	0.00	0.00	10.00
Site 1	Chute Location	10.00	5.00	10.00
Site 1	Steel Storage area	10.00	-5.00	10.00
Site 1	Refuse Container (Non-Inert Waste)	10.00	5.00	0.00
Site 1	Refuse Container (Inert Waste)	8.00	8.00	0.00
Site 2	Landfill	50.00	5.00	0.00
Site 3	Recycler			

Resource Transit Info Sys			
GEN_LB_T	Site 1-Chute Location	Site 1-Working Platform	Triangular(1.00,2.00,1.50)
GEN_LB_S	Site 1-Steel Storage area	Site 1-Working Platform	Triangular(0.50,1.50,1.00)
GEN_LB_S	Site 1-Working Platform	Site 1-Steel Storage area	Triangular(0.60,1.00,0.80)
GEN_LB_S	Site 1-Chute Location	Site 1-Steel Storage area	Triangular(0.80,1.20,1.00)

Fig. 6. (Top) Snapshot of the animation of the waste handling simulation model in the computer-generated site layout view; (middle) location set defined for the site system; and (bottom) resource transit information system

animation of the waste-handling model as of our case study. The computer-generated site layout view for animation is based on the *location set* defined for the site system (shown in the middle of Fig. 6). The animation is particularly instrumental in validating the simulation model by replaying the activity sequence and the resource transit between different locations in the site. The activity times are defined with triangular distributions (minimum, mode, maximum,) as summarized in Table 2. Additional resource transit information, which is not represented as duration of activities of the SDESA model (Figs. 4 and 5), is specified in the "resource transit information system" attached to the SDESA model (lower part of Fig. 6). For instance, the activity duration for "2: Transport" (Fig. 4) represents the time for a timber laborer to transit from the working platform location to the refuse chute location and is modeled as a triangular distribution (minimum=1.5 min, mode=2 min, maximum=3 min); while the transit time for a timber laborer to return from the refuse chute location to the working platform location follows a different triangular distribution (minimum=1 min, mode=1.5 min, maximum=2 min), which is specified in the resource transit information system for sampling during simulation.

With the SDESA simulation model, we can readily design and carry out simulation experiments to evaluate, analyze, and optimize the efficiency and cost effectiveness of a given waste-handling method being postulated. In contrast with a "static" de-

Table 2. Activity Duration Definitions for Simulation Analysis

		Time (min)		
Activity number	Work package	Triangular distribution (minimum)	Triangular distribution (mode)	Triangular distribution (maximum)
1	Collect	3	5	7
2	Transport	1.5	2	3
3	Dump	0.5	0.7	0.9
4	Collect	3	5	7
5	Transport	1.5	2	3
6	Dump to store	1	1.5	2
7	Load	4	5	6
8	Transport	55	60	65
9	Dump to landfill	10	15	20
10	Down thru chute to refuse container	0.3	0.5	0.7
11	Load	2	3	4
12	Transport to recycler	25	30	35
14	Load stored steel waste	2	3	4
15	Transport	1	1.5	2
16	Dump	0.5	0.7	0.9
17	Down thru chute to refuse container	0.3	0.5	0.7

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Table 3. Simulation-Predicted Waste Pick Up Times Based on the First Optimum Option

Type of waste	Truckload ID number	Pick up time (minutes after simulation starts)
Timber/noninert waste (by refuse truck)		
	1	17
	2	28
	3	39
	4	54
Steel/inert waste (by steel collection vehicle)		
	1	78
	2	99

piction of the waste-handling methods by the mapping model (as in Fig. 2), the simulation model provides a "dynamic" representation of the interactions, complexities, and uncertainties in the system. This makes it possible to gain insight into their effects on system performances and design the optimal system configuration, as elaborated in the next section.

Analysis of Simulation Results

In our case study, three variables are identified as being significant to planning the site waste handling efforts, and they are (1) the number of laborers handling timber waste; (2) the number of laborers handling steel waste; and (3) the number of storage blocks temporarily holding steel waste. Based on the likely values of the three variables, we designed and simulated a total of 250 different scenarios. For each scenario, the simulation results were averaged over 100 Monte Carlo replications, which required 30 s computer time on a Pentium III 863 MHz IBM PC. The details of the simulation input and output are given in Table 4.

It was found that at least three timber laborers were needed in order to finish processing all timber waste in the first hour (before the refuse chute was switched to handling steel waste). Hence, the scenarios with two or one timber laborers were deemed infeasible. For those scenarios with nine plus storage blocks and two plus steel laborers (and three plus timber laborers), the total waste-handling time was guaranteed to fall under the preset 100-min target. However, nine plus temporary storage blocks would occupy excessive space in the congested floor area, thus rendering those scenarios impractical.

Three out of the 250 postulated scenarios were identified as the optimum options, namely: (1) three timber laborers, five steel laborers and four storage blocks, resulting in an averaged total handling time of 99.69 min; (2) three timber laborers, four steel laborers, and eight storage blocks, giving a 94.53 min total handling time; and (3) three timber laborers, two steel laborers, and nine storage blocks, giving a 95.00 min total handling time. It was observed that the number of timber laborers was fixed as three in the three optimum scenarios; while the use of more storage blocks would reduce the number of steel laborers as needed. Therefore, the first option would be preferred (more steel laborers and less storage blocks) if the site was more confined by the space available in the working area. On the other hand, the third option (less steel laborers and more storage blocks) would prevail if the

Table 4. Details of Simulation Input and Output of Postulated Scenarios

Number of GEN_LB_S	Number of GEN_LB_T 1	2	3	4	5
(a) Three storage blocks					
1	INF	INF	199.03	198.25	198.02
2	INF	INF	165.31	164.77	165.01
3	INF	INF	134.96	134.28	134.61
4	INF	INF	116.57	116.37	116.60
5	INF	INF	104.17	103.71	103.91
(b) Four storage blocks					
1	INF	INF	182.78	183.27	183.03
2	INF	INF	153.53	153.25	153.28
3	INF	INF	151.51	151.54	151.82
4	INF	INF	125.51	125.61	125.22
5	INF	INF	99.69	99.57	99.64
(c) Five storage blocks					
1	INF	INF	168.07	167.21	167.81
2	INF	INF	141.93	142.24	142.02
3	INF	INF	139.52	140.27	139.51
4	INF	INF	129.62	129.82	129.74
5	INF	INF	111.65	111.71	111.95
(d) Six storage blocks					
1	INF	INF	152.46	152.46	152.10
2	INF	INF	129.85	130.20	130.09
3	INF	INF	128.23	128.14	128.18
4	INF	INF	117.91	118.11	118.15
5	INF	INF	113.83	113.77	114.23
(e) Seven storage blocks					
1	INF	INF	143.41	143.90	143.54
2	INF	INF	118.57	118.10	118.82
3	INF	INF	116.26	116.41	116.78
4	INF	INF	106.21	106.50	106.21
5	INF	INF	102.29	102.04	102.23
(f) Eight storage blocks					
1	INF	INF	138.33	138.59	137.53
2	INF	INF	106.74	106.56	106.79
3	INF	INF	104.85	104.77	104.83
4	INF	INF	94.54	94.82	94.71
5	INF	INF	90.28	90.50	90.54
(g) Nine storage blocks					
1	INF	INF	132.57	132.45	132.80
2	INF	INF	95.01	94.99	95.28
3	INF	INF	93.01	93.13	93.02
4	INF	INF	82.83	82.85	83.06
5	INF	INF	80.99	80.96	80.97
(h) Ten storage blocks					
1	INF	INF	126.40	126.43	126.20
2	INF	INF	83.47	83.43	83.45
3	INF	INF	81.44	81.36	81.33
4	INF	INF	72.29	72.31	72.37
5	INF	INF	72.32	72.21	72.36
(i) Eleven storage blocks					
1	INF	INF	120.47	120.68	120.66
2	INF	INF	71.70	71.60	71.84

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Table 4. (*Continued.*)

Number of GEN_LB_S	Number of GEN_LB_T				
	1	2	3	4	5
3	INF	INF	71.53	71.67	71.83
4	INF	INF	71.64	71.80	71.85
5	INF	INF	71.73	71.84	71.54
(j) Twelve storage blocks					
1	INF	INF	115.20	114.98	115.25
2	INF	INF	58.32	58.05	58.15
3	INF	INF	53.55	39.90	39.16
4	INF	INF	53.35	38.99	34.60
5	INF	INF	53.27	38.80	34.49

Note: INF=infeasible scenarios in which the timber waste could not be disposed of before the refuse chute switched for handling steel waste as the second hour started.

site management was more obliged to save labor cost. In our case study, we chose the first option and ran the simulation to predict the times for pickup trucks to arrive on site and haul wastes away from the site. The results are listed in Table 3. Note that the timely removal of waste from the site is conducive to smooth waste-handling operations as designed, subject to limited volume capacities of waste containers and site space available.

Conclusion

A blend of inert and noninert wastes generated from construction sites requires costly off-site treatment for segregating the reusable inert portion. As a result, construction and demolition wastes are largely deemed economically infeasible for recycling or reuse in reclamation and site formation works, and instead, are disposed of in landfills. This research has been focused on modeling waste-handling processes in construction, with particular emphasis on mapping and simulation of on-site waste sorting processes. The research has proposed an application framework for guiding the mapping and simulation of waste-handling processes and further assessing the cost effectiveness of on-site waste sorting efforts under practical site constraints (such as labor resource availability, time control on refuse chute usage, and limited working area space in a building site). The connection has been established between the mapping and simulation techniques in the context of modeling waste-handling processes in construction sites, such that the flowchart resulting from the mapping technique could serve as convenient model input to facilitate the creation of a dynamic operations simulation model. A case study of the on-site waste sorting method with one refuse chute for waste classification has demonstrated the complete application framework beginning from process mapping, mapping-to-simulation-model conversion, through to method optimization based on valid simulations. Although the case study is based on experiences and conditions on a typical building site in Hong Kong, it describes waste-handling processes in building sites in general, and hence, can be readily adapted to reflect local practices in other places. The proposed application framework, which is based on a straightforward process mapping technique and a simplified discrete-event simulation approach, holds the potential of becoming a generic methodology that can assist practitioners in improving waste management practices in construction.

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