Materials Handling System Simulation in Precast Viaduct Construction: Modeling, Analysis, and Implementation

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Abstract: The interactive, complicated system environment of a construction site renders conventional site layout planning and scheduling techniques to be inadequate in coping with materials handling system design in construction. In this paper, we present a university-industry joint endeavor for improving the effectiveness of the materials handling system on a precast viaduct construction project in Hong Kong by implementing the simplified discrete-event simulation approach (SDESA) along with its computer platform resulting from recent research. How to apply the simulation methodology of SDESA is elaborated step by step. Particular emphasis is placed on procedures of establishing a simulation model, validation of the simulation model, design of simulation experiments, and analysis of simulation results. With process flowchart, site layout plan, and process animation produced in a view-centric simulation environment, it is straightforward to establish, validate, and communicate the operations simulation. The research team convinced the project director, as well as field managers, of the functionality and effectiveness of operations simulation. The knowledge derived from simulation added to experiences of site managers in materials handling system design. With the aid of simulation, even junior engineers would be capable and confident to draw up an actionable construction plan that would lead to enhancement of cost effectiveness and productivity in the field.

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Introduction

Materials Handling System Design in Construction

The construction of a building or an infrastructure facility entails concerted efforts for transporting, storing, assembling, placing building materials (such as concrete, wood, steel, precast or prefabricated assembly units) within a confined site space by following specific construction technology. Hence, a construction site can be regarded as a *materials handling system*, the efficiency of which dictates whether the productivity and economy objectives of the whole project can be attained (Halpin and Woodhead 1998). As material storages occupy the site space and provide buffers between multiple work flows in the construction system, design and evaluation of a materials handling system is concerned with how to lay out storage areas at the site and how to expedite and sequence material deliveries so as to match up with construction activities (Thomas et al. 1989). In general, work space highly depends on the equipment and materials involved in production activities and changes as construction work progresses (Tommelein et al. 1992). Insufficient work space available on site results in productivity loss, potential safety hazards, and poor workmanship (Riley and Sanvido 1995). Thus, a good layout of storage spaces and transit paths for materials handling contributes to the overall construction operations efficiency (Li et al. 2001). Two streams of construction planning techniques are in close connection with materials handling system design, namely, (1) *material inventory planning*, which aims to optimize onsite material storage location and size (Thomas et al. 1989); and (2) *site layout planning*, which is concerned with how to place temporary facilities within the confines of a construction site so as to achieve efficiency and safety in movement of resources (Tommelein and Zouein 1993).

A construction project is conventionally planned by articulating activities and their dependencies into a network diagram, then estimating duration, and assigning resources to each activity for critical path analysis. On one hand, the *critical path method* (CPM) is effective for (1) displaying technological relationships among activities contained in the work breakdown structure of a complex project; and (2) identifying activities along the critical path so as to control total project duration (O'Brien and Plotnick 2006). On the other hand, CPM falls short on addressing (1) the dynamic, repetitive nature of construction operations; (2) space and resource availability constraints; and (3) intricate logical relationships and complex interdependencies among various components within a project system (Lu 2003). In reality, field managers have been relying on rules of thumb, past experience, and intuition to draw up action plans in response to different situations. In a similar way, the current practice of site layout planning is largely to apply a planner's experience and common sense to allocate and manage site space by foreseeing different needs of

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J. Constr. Eng. Manage., 2008, 134(4): 300-310

space use—including material deliveries, staging areas, and locations of major equipment and plants on site—and preparing a two-dimensional chart at the beginning of a project (Tam et al. 2002). In short, the interactive, complicated system environment of a construction site renders conventional site layout planning and scheduling techniques to be inadequate in coping with the materials handling system design in construction (Tommelein and Zouein 1993; Horman and Thomas 2005). Considerable research efforts have been made in this regard.

Previous Related Applications

Based on site data collected in two steel erection projects, Thomas et al. (1989) found that contractors without proper material management practices could incur three times more productivity loss. Thomas et al. (1999) further evaluated the loss of labor productivity due to uncoordinated delivery methods and improper material management practices from observation of three steel erection projects. Thomas et al. (2005) generalized 18 principles for material management applicable to three categories of storage areas: namely, (1) the semipermanent storage area; (2) the staging area; and (3) the workface area. Note for each category of storage areas, relevant principles describe functions and provide guidance on material inventory planning. Yet, rigorous quantitative analyses are lacking to support those rules and address such issues as (1) how far those areas should be located away from the working area; and (2) how much inventory should be held in storage areas of different types.

Riley and Sanvido (1997) generalized patterns of construction-space use in multistory buildings and conceptualized a space planning model to cover (1) identifying required spaces; (2) generating a site layout; (3) sequencing activities; and (4) resolving conflicts. Elbeltagi et al. (2004) resorted to the use of mathematical programming and genetic algorithms to optimize the positioning of temporary storage areas. Note their optimization analysis required “subjective” input of user-defined closeness relationship values (weights) and unit transportation costs. Guo (2002) proposed procedures and criteria for identifying and resolving space conflicts in construction planning. The spatial need of construction activities for material storage was incorporated into the CPM schedule.

It is noteworthy that in deriving the site layout plan or the space use schedule, previous research endeavors have highly simplified or even overlooked dynamic interactions inherent in construction operations. This is mainly attributable to limitations of underlying analytical methods being applied, e.g., linear programming in Elbeltagi et al. (2004) and CPM in Guo (2002). The lack of an accepted practical technique for evaluating the efficiency of a chosen materials handling system design makes it difficult to choose objectively between possibilities (Li et al. 2001). An alternative attempt in the search for better site layout design was reported in Li et al. (2001), who drew upon a quantitative material flow network model, which required tedious, manual data-gathering efforts at the microoperation level for evaluating the cost efficiency of a certain site layout option in terms of the “total material flow time.”

Meanwhile, modeling capabilities and ease of use of simulation tools have been evolving from the original CYCLONE (Halpin 1977), to the more recent development of STROBOSCOPE featuring programmability and extensibility (Martinez 1996), to the simulation environment of SIMPHONY that is conducive to rapid customization of special-purpose simulation tools (Hajjar and AbouRizk 2003). Simulation modeling holds high potential for (1) facilitating productivity level estimation for complicated processes; (2) improving repetitive process scheduling; and (3) planning adequate resource assignment that minimizes time and cost (Gonzales-Quevedo et al. 1993). A simulation application related to materials handling system design in construction is presented in Tommelein (1999). A systematic, simulation-based approach was employed to facilitate the positioning and sizing of material storages. A STROBOSCOPE simulation model was built to assess (1) the traveling and waiting times tolerable to the crews in fetching small tools and consumable materials; and (2) the cost of adding capacity to the tool room. With a hypothetical case, the research demonstrated the possibility of establishing a simulation model to represent the complexities, uncertainties, and interactions inherent in the materials handling system.

Simplifying Simulation Methodology

Despite advances made in construction research, the use of simulation in construction practices has generally been random and sporadic, and numerous attempts to interest major construction companies in simulation as a productivity-enhancing means have proved unsuccessful (Halpin 1998). The difficulty of promoting simulation in construction is also attributed to the analytic aspect of the technique itself and the time required in learning and applying simulation tools (Halpin 1998; Shi and AbouRizk 1997; Oloufa et al. 1998). As a matter of fact, being able to harness the power of simulation requires construction practitioners to invest considerable time and dedicated learning in (1) developing cognitive skills of observing, analyzing, and depicting site operations as needed for simulation modeling; and (2) mastering special knowledge of computer use, software specifications, and statistics (Lu and Wong 2007).

In recent years, a great deal of research has been undertaken into bridging the gap between research and application in construction simulation by simplifying simulation methodologies while retaining essential modeling functionalities. Representative developments include (1) resource-based approaches, which generate full-scale, complex simulation models through linking atomic models for particular resource operating processes (Shi and AbouRizk 1997) or preprogrammed construction resources (Oloufa et al. 1998); (2) activity-based approaches, which mimic the commonly practiced CPM in construction planning by reducing modeling constructs of general-purpose simulation tools to activity blocks (Shi 1999; Lu 2003); and (3) special-purpose simulation approaches, which develop object-oriented simulation constructs and modeling environments native to specific construction domains so as to allow a domain expert—being a construction engineer—to conduct simulation studies with minimal learning time (Hajjar and AbouRizk 2003).

To adapt the process-interaction simulation paradigm to better cater to construction simulation needs and simplify construction operations modeling, Lu (2003) proposed a construction simulation technique, called the simplified discrete-event simulation approach (SDESA). SDESA was verified and implemented in simulation of Hong Kong’s one-plant-multisite concrete plant operations (Lu et al. 2003). An interruption model was later embedded in SDESA to accurately account for effects of concurrent operational interruptions upon system performance (Lu and Chan 2004). An elaborate comparison of SDESA and the popular PROMODEL was made based on typical construction applications (Lu and Wong 2007). It is found that SDESA can adequately depict construction operations, requiring less learning and modeling efforts. In an attempt to effectively model resources’ transit

J. Constr. Eng. Manage., 2008, 134(4): 300-310

among various activity locations at a construction site, Lu et al. (2007) enhanced the algorithm formation and model structure of SDESA, resulting in the development of a generic process mapping and simulation methodology for integrating site layout and operations planning in construction. In order to contrast SDESA with the established activity cycle diagram-based methodology, a scraper-pusher earthmoving problem was translated into a SDESA model and a STROBOSCOPE model, respectively. Executing the two models under identical definitions of operations logic and activity times resulted in the same simulation outputs. However, the activity cycle diagram model appeared unwieldy for portraying the pusher's transit between various locations; as a result, forming up the STROBOSCOPE model for typical construction processes demanded more time and efforts than SDESA (Lu et al. 2007).

Research Overview

In this paper, we present a university-industry joint endeavor for improving effectiveness of the materials handling system on a precast viaduct construction project by implementing SDESA. The remainder of the paper first describes the material inventory problem in the precast viaduct project, followed by elaboration of how to apply the simulation methodology of SDESA as illustrated with the case study of designing, evaluating, and improving the materials handling system in precast viaduct construction. Particular emphasis is placed on procedures of establishing a simulation model, validation of the simulation model, design of simulation experiments, and analysis of simulation results. In addition, feedback as to implementation of the simulation results by the participating contractor is discussed. In the conclusion, research contributions are recapitulated and experiences from this university-industry joint study are shared.

Case Study in Precast Viaduct Erection

Project Background and Problem Statement

On the Deep Bay Link North Project, over 227 spans of posttensioned viaduct were erected to form a major portion of a new artery connecting Hong Kong to Shenzhen—the manufacturing and business hub in southern China. The stepping girder precast construction method was utilized in order to accelerate span erection progress and minimize interferences with the existing traffic on roads and railways crossing the viaduct under erection. A complete cycle of one span viaduct erection was comprised of three main steps: namely, (1) placing precast segments in position as designed by use of a giant gantry riding over two piers of the current span, (2) concreting stitching joints followed by posttensioning precast segments, and (3) advancing the stepping girder to the next span by using a group of powerful hydraulic jacks. Fig. 1 shows the giant gantry of the stepping girder.

Upon calibrating the alignment of the stepping girder, erection of the precast segments started. A tractor hauled one segment from the staging area in the site (i.e., a temporary storage close to the current span) to the workface area under the current span. The spreader beam (a mechanical hoist attached to the stepping girder) hoisted the segment off the tractor's trailer and onto its designed position of the viaduct span. The erection cycle was completed after the segment was placed in position and firmly locked onto the hanging bars of the stepping girder. Once all the segments for the current span were placed, epoxy was applied to glue them

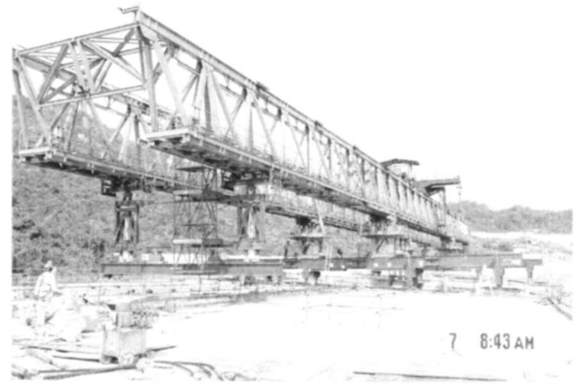

Fig. 1. Giant gantry of the stepping girder for erecting precast segments

together, which also served as a lubricant to facilitate ensuing operations of segment installation. Watertight joints were formed as the epoxy hardened. The gaps between the two end segments and the two piers were then stitched with ready-mixed concrete. Adequate curing of "stitching" concrete required 12 h before all the precast segments could be posttensioned into one complete span of viaduct. At last, the stepping girder was disengaged from the current span, ready to advance to the next one.

In this Hong Kong project, all the precast segments were fabricated in the neighboring Guangdong province of mainland China, and were only allowed to be hauled to the Hong Kong site during the night time—as restricted by highway traffic regulations. In some spans along the viaduct, the workface area under the span was spacious enough to store all the segments within the handy reach of the crew, while for many others it became too narrow to freely move a heavy-duty crawler crane around. The site management realized that it was unjustifiable and unsafe to strive for sufficient storage space for accommodating up to 17 precast segments in the close vicinity of many spans under construction ($12\ \mathrm{m} \times 2.5\ \mathrm{m} \times 2.8\ \mathrm{m}$ each segment, as shown in Fig. 2). Actually, in a precast construction site, it is likely to have several activities concurring near the workface area; thus, the congestion problem is commonplace, presenting safety hazards and hampering construction productivity (Low and Chuan 2001).

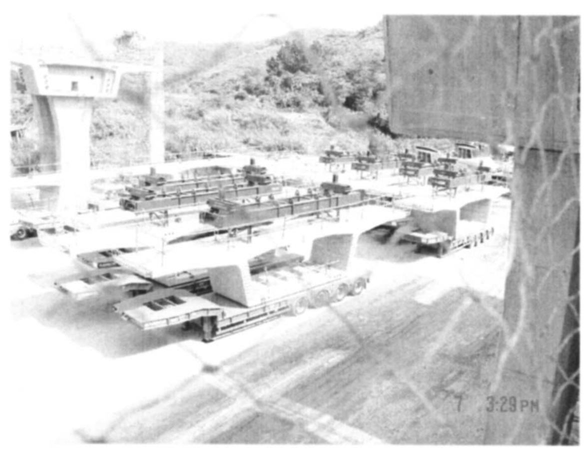

Fig. 2. Bulky precast segments ($12\ \mathrm{m} \times 2.5\ \mathrm{m} \times 2.8\ \mathrm{m}$ each) temporarily stored near the working span

J. Constr. Eng. Manage., 2008, 134(4): 300-310

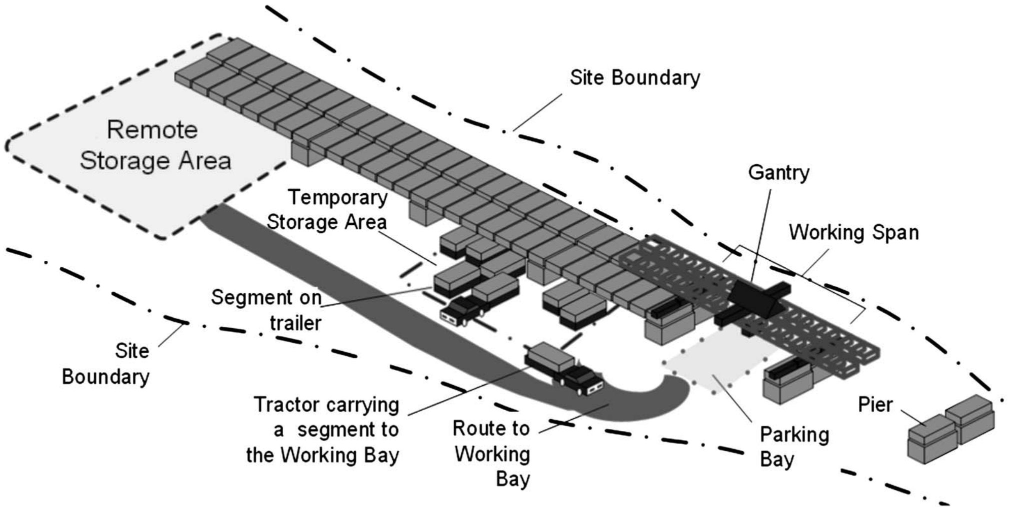

Fig. 3. Alternative materials handling system design: precast segments partially stored at a relatively remote storage area, hauled to the working span by tractors

To alleviate congestion around the temporary storage area near the working span, an alternative solution was to store some precast segments at a relatively remote storage area, as illustrated in Fig. 3. However, in postulating such an alternative, it was not straightforward for site management to address two questions with certainty: (1) How far away the remote storage area would be located so as to ensure a smooth, efficient segment erection process; (2) how many precast segments could be stored there such that the targeted cycle duration would be maintained. Note, any disruption to site progress would translate into considerable productivity and economical losses. For instance, any logistical hiccups in supplying precast segments might disrupt the rhythm of construction, potentially causing the expensive specialist crew (manpower and plant) to idle at site. In consequence, the five-day cycle duration as scheduled for erecting one span could be prolonged. Moreover, this might produce negative ripple effects on progress of succeeding spans and completion of the whole project. According to the CPM plan obtained from the site, tasks concerning precast segment installation resided along the critical path of the project schedule. As such, a one-day delay to the target cycle duration on a particular span would lead to a one-day extension to the contract period, potentially obliging the contractor to pay for liquidated damages.

In designing the materials handling system for the precast viaduct project, we identified four relevant factors; they are (1) the storage capacity of the remote storage area (the semipermanent storage area remote from the working span), which supplemented the temporary storage area immediate to the working span; (2) the positioning of the remote storage area (described in terms of tractor transit time from the remote storage area to the working span); (3) the number of tractors rented for hauling precast segments from both temporary and remote storage areas to the working span; and (4) the number of batches in delivering precast segments to the site and the associated delivery times (the precast supplier delivered all the segments for one span in one batch before site erection operations started or in two batches over the first two nights of the five-day cycle). Through simulation modeling and simulation-based experiments, we assessed effects of the above four factors on the cycle duration required for installing one span viaduct.

The simulation study was based on direct site observation of precast segment installation cycles, interviews with experienced site staff, and assessment of site records including the method statement, the work schedule, and daily reports. The following information was obtained as model inputs: (1) CAD illustrations for construction processes; (2) the work breakdown structure for viaduct span erection; (3) time and resource requirements for major activities; (4) site constraints on resource availability and working hour; and (5) any process interruptions. Note, constraints of working hours (08:00–23:00 in two shifts, Mon–Sat) and regular activity interruptions (i.e., lunch/dinner breaks, nonworking hours at night) applied to all site activities, except for curing of “stitching” concrete (requiring twelve hours). In modeling activity interruptions of various types, the present case study took advantage of SDESA’s flexible functionalities for handling multiple concurrent operational interruptions in construction activities—which can be prescheduled or random (Lu and Chan 2004).

The remainder of this paper will focus on how to implement the SDESA simulation methodology in a practical setting, and explain in detail on modeling constructs, modeling steps, and application guidance in the context of the precast viaduct construction case study.

Application of SDESA Simulation Methodology

Terminologies

SDESA characterizes construction activities into (1) *transit activities*; and (2) *production activities*. A *transit activity* engages a machinery or manpower resource for certain time duration in moving a material unit from an origin location to a destination location in the site space. For instance, in the transit activity of “*haul segment from storage to working span*,” a tractor moves a precast segment from the storage area to the working area that is under the viaduct span being built. In contrast with a *transit activity*, a *production activity* occurs at one relatively fixed location involving the use of manpower and machinery resources for a certain time duration to place a material unit. SDESA also explicitly defines *disposable resources* for representing either materials or signals, which are generated as intermediate products by one activity, and requested and consumed by another. Note, as op-

J. Constr. Eng. Manage., 2008, 134(4): 300-310

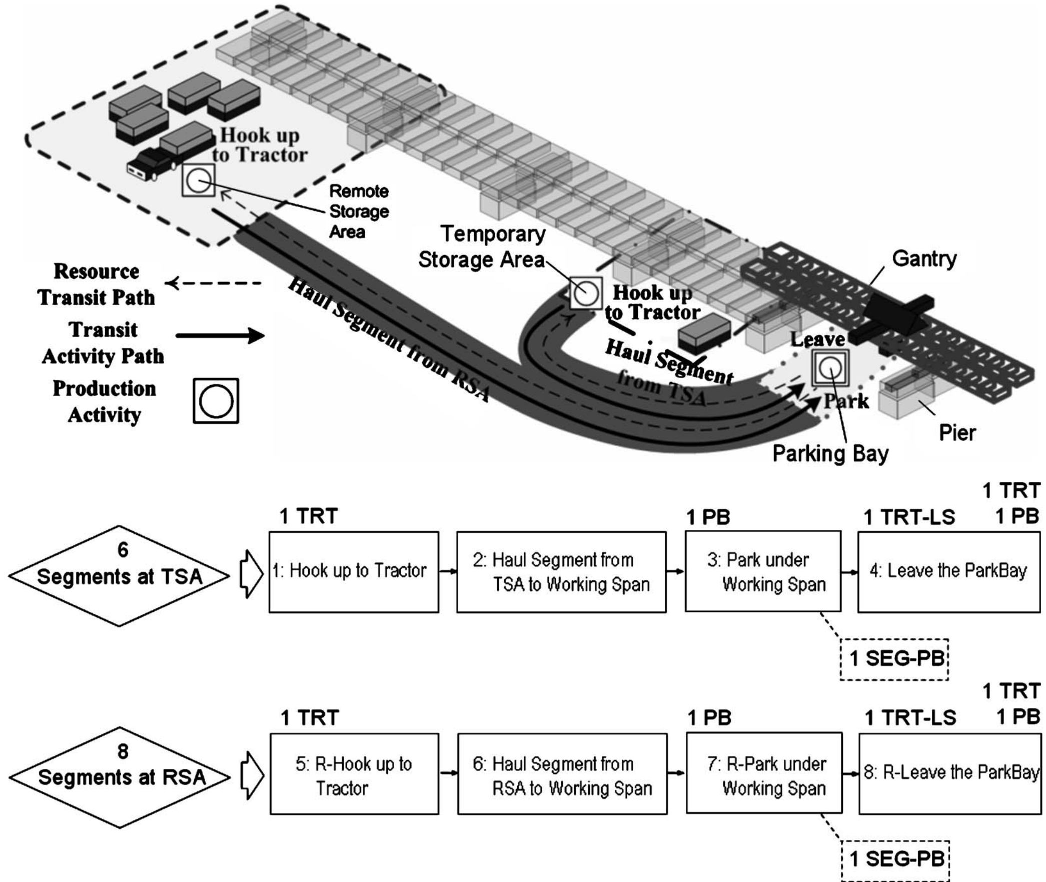

Fig. 4. (a) Site layout and operations illustration; (b) SDESA model for segment hauling work flows

posed to common manpower or machinery resources, *disposable resources* can be utilized for one time only and serve as the logical linkage between different activities and work flows (Lu 2003).

The SDESA modeling methodology is reminiscent of the resource-loaded CPM: Activities are defined with time and resource requirements identified, followed by articulation of activities into work flows according to construction technology. However, activity definition in SDESA differs from CPM by (1) highlighting activity locations; (2) specifying generation of disposable resources; and (3) adding *disposable resources* to resource requirements. Moreover, through associating a diamond node with the first activity of each work flow, a SDESA model specifies what type of work units (*flow entities*) and how many are to be handled by each work flow.

Modeling Procedures

Application steps of SDESA modeling are elaborated as follows, illustrated with the case of precast viaduct construction:

1. Depict main work flows in the construction system by identifying key activity locations in the site space (as denoted with *location circles*), and defining activities comprising each work flow. In Fig. 4, locations for the remote storage area, the temporary storage area, and the parking bay under the current span are marked with circles. Work flows for moving precast segments (1) from the remote storage area to the working span; and (2) from the temporary storage area to the working span are highlighted with directional arrows, which can be further converted into two lines of activities in the SDESA model (bottom of Fig. 4). At the temporary storage area, the work flow consisting of Activity Nos. 1 to 4 starts with hooking up a tractor (TRT) with a trailer loaded with one segment at the temporary storage area. The tractor then hauls the segment from the temporary storage area to the working span. When the parking bay (PB) under the span is empty, the tractor pulls in under the working span to unload the segment. Upon the moment that the segment is lifted up by the spreader beam of the gantry, the tractor leaves the parking bay. In a similar way, the second work flow for hauling segments from the remote storage area to the working span can be interpreted. Note, in Fig. 4, it is assumed that 14 segments form the current span; six segments are placed in the temporary storage area while the remaining eight are stored in the remote storage area.
2. Identify all the resources that need to be matched and used on each activity, including manpower and machinery resources and disposable resources. As for activity "*1: hook up to tractor*" (Fig. 4), "*1 TRT*" is marked in the top left corner of the activity block, indicating a tractor (TRT) is required to execute the activity; the tractor is released at the end of activity "*4: leave the parkbay*," which is represented by "*1 TRT*" being marked in the top right corner of that activity. Similarly, the unoccupied PB is the resource required to trigger the start of activity "*3: park under working span*." The parking bay is only released together with the tractor at the end of activity "*4: leave the parkbay*." Note, the prefix "+" signifies the disposable nature of a resource. "$1+TRT-LS$"—representing "*tractor leaving signal*"—is

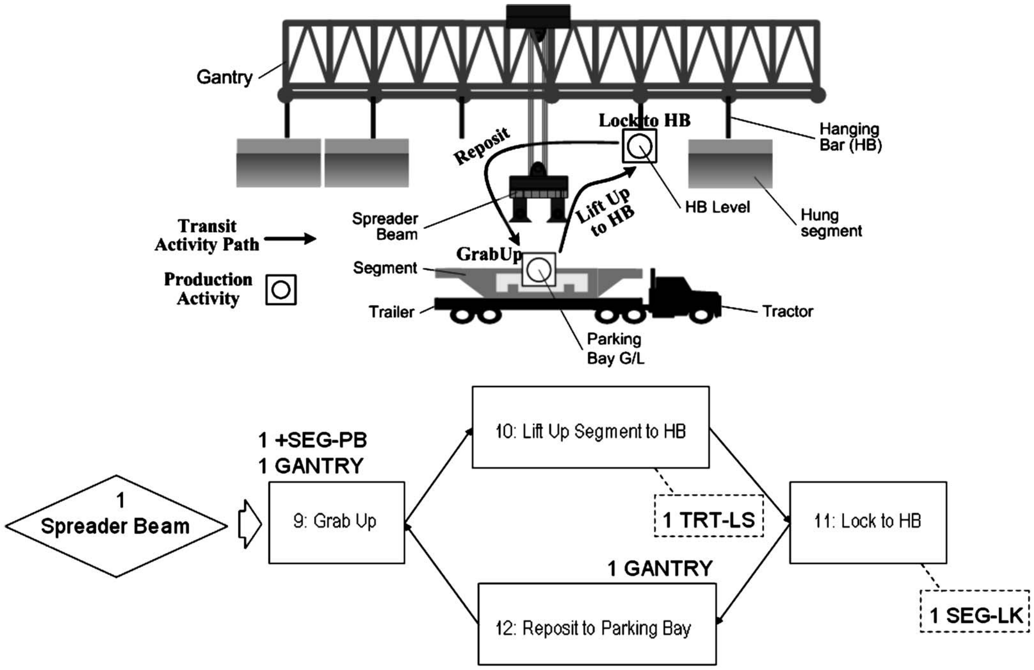

Fig. 5. (a) Process illustration; (b) SDESA model for segment erecting work flows

also specified as resource requirement for activity "*4: leave the parkbay*." Note the "*tractor leaving signal*" is a disposable resource generated by activity "*10: lift up segment to HB*" in the segment erection work flow (as discussed in the ensuing paragraph). Another disposable resource "+*SEG* − *PB*" is produced upon finishing activity "*3: park under working span*;" it indicates one precast segment has been delivered and is ready for installation. The disposable resource "+*SEG* − *PB*" is requested to trigger the start of activity "*9: grab up*" in the segment-erecting work flow. The segment-erecting work flow is illustrated in Fig. 5, which is represented with a looping model structure in SDESA. The spreader beam of the gantry—analogous to the hopper of a tower crane—undergoes the cyclic process of segment erection: It lifts a segment off the tractor and places it onto the hanging bars of the gantry; afterwards, the spreader beam repositions itself and returns for handling the next segment. Four activities make up the looping work flow, as shown in the bottom of Fig. 5. The initial activity "*9: grab up*" requires not only the gantry resource, but also the availability of one segment delivered at the parking bay—which is represented by the disposable resource "+*SEG* − *PB*." On one hand, "+*SEG* − *PB*" is generated at the end of "*park under working span*" activities in segment-hauling work flows previously described. On the other hand, the disposable resource "+*TRT* − *LS*"—generated at the end of the "*10: lift up segment to HB*" activity (Fig. 5)—is requested for invoking the two "*leave the parkbay*" activities in the segment hauling work flows (Fig. 4). In order to tally the number of segments already locked onto their final positions, another disposable resource of "+*SEG* − *LK*" is generated at the end of activity "*11: lock to HB*." Consequently, accumulation of 14 such disposable resources will signal the end of the segment erection process and trigger the start of posterection operations (mainly "stitching" concreting and posttensioning), which are modeled with six activities (activities 13 through 18) in the SDESA model shown in Fig. 6. Two particular observations are made as for SDESA modeling: (1) the two segment-hauling work flows are logically related to one another through requesting shared resources defined in the SDESA model (i.e., the tractor and the parking bay); and (2) the segment-hauling work flows are logically linked with the segment-erecting work flow by use of disposable resources (i.e., "+TRT − LS" and "+SEG − PB").

3. Specify activity time in statistical distributions based on data collected from the site. Any additional transit time taken by a *resource* in serving different activities at different locations can be defined in the *resource transit information system* (*RTIS*) of the simulation model. In our case, the tractors are shared resources serving two segment hauling work flows. Upon releasing of a tractor at the end of unloading activities at the parking bay, the tractor returns to one of the two storage areas, with corresponding transit time distributions specified in RTIS of the SDESA model (Fig. 7). Similar to activity

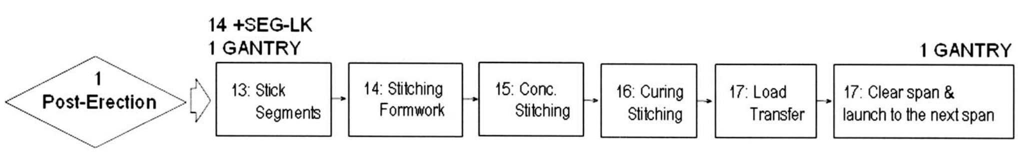

Fig. 6. SDESA model for posterection operations

J. Constr. Eng. Manage., 2008, 134(4): 300-310

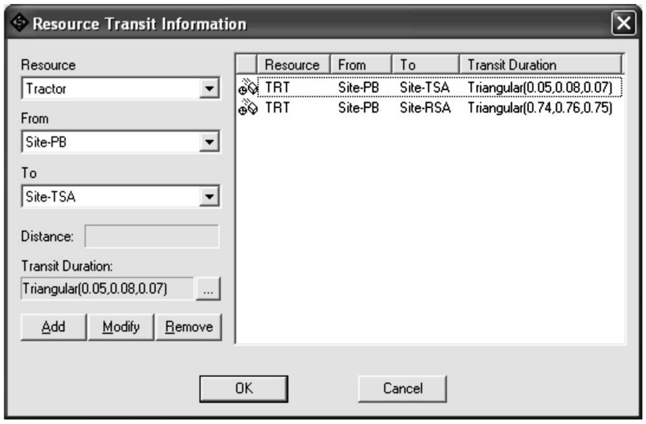

Fig. 7. Resource transit information system (RTIS) in SDESA computer platform

duration distributions, those transit time distributions are sampled during simulation for modifying the status of the tractor involved (i.e., its current location and available time).

4. Initialize quantities and arrival times of the *work units* to be handled in each work flow in a *diamond block*, which is connected to the first activity of a work flow, and initialize the type and quantity of resources available (including disposable resources) in the *resource pool* of the simulation model. In our case study, the number of segments at the two storage areas along with their delivery times is initialized for the two segment hauling flows (six and eight segments for the temporary and remote storage areas, respectively, in Fig. 4); while one spreader beam is initialized for the segment erecting work flow (Fig. 5). Fig. 8 gives the complete SDESA model consisting of four work flows and the resource pool. To mirror the actual site situation, one gantry, one parking bay under the working span, plus three tractors were initialized in the resource pool of the SDESA model, while quantities of three disposable resources ("+SEG−PB," "+TRT−LS," and "+SEG−LK") were set to zero at the initial state of the simulation (see the *Resources* table in Fig. 8).
5. Map activity location definitions onto their corresponding positions in a site layout model so as to complete the formulation of simulation model in the site layout view (Fig. 9). Our prototype computer platform automatically represents a *production activity* with a square block at a *location circle* and a *transit activity* with a line section connecting two *location circles*. Since more than one activity may overlap in space, various colors are applied on a square block or a line section in order to differentiate various activities during process animation. In the animation view, currently activated activities are highlighted (thickened lines or squares) and moving resources are simply portrayed as circular dots, as illustrated in Fig. 9.

Base Case Model

The following assumptions were made as advised by site management: (1) all the segments of one span were delivered in one batch before site erection operations started; (2) in simulation, precast segments stored at the temporary storage area were first hauled to the working span for installation, followed by hauling the segments stored at the remote storage area; and (3) to avoid double handling, the temporary storage area would not serve as a buffer between the remote storage area and the working span (in other words, segments in the remote storage area would be hauled directly to the working span for installation.)

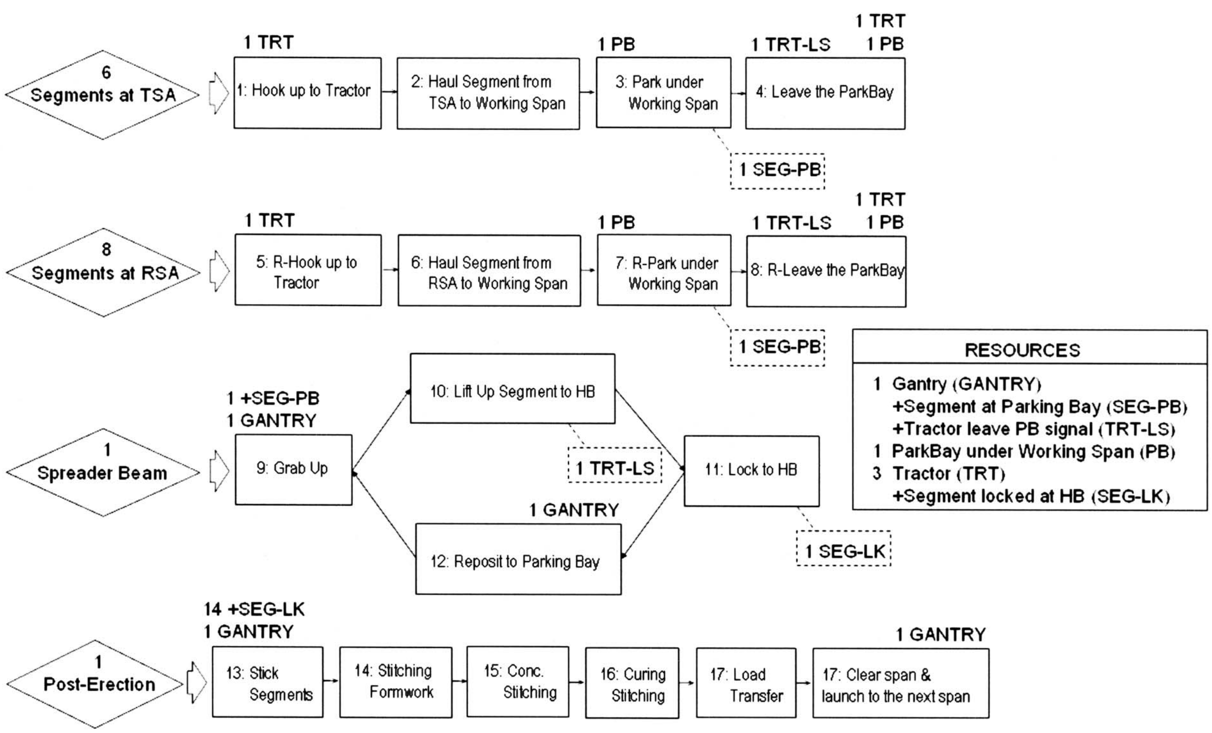

Fig. 8. Complete SDESA model for one-span viaduct installation operations

J. Constr. Eng. Manage., 2008, 134(4): 300-310

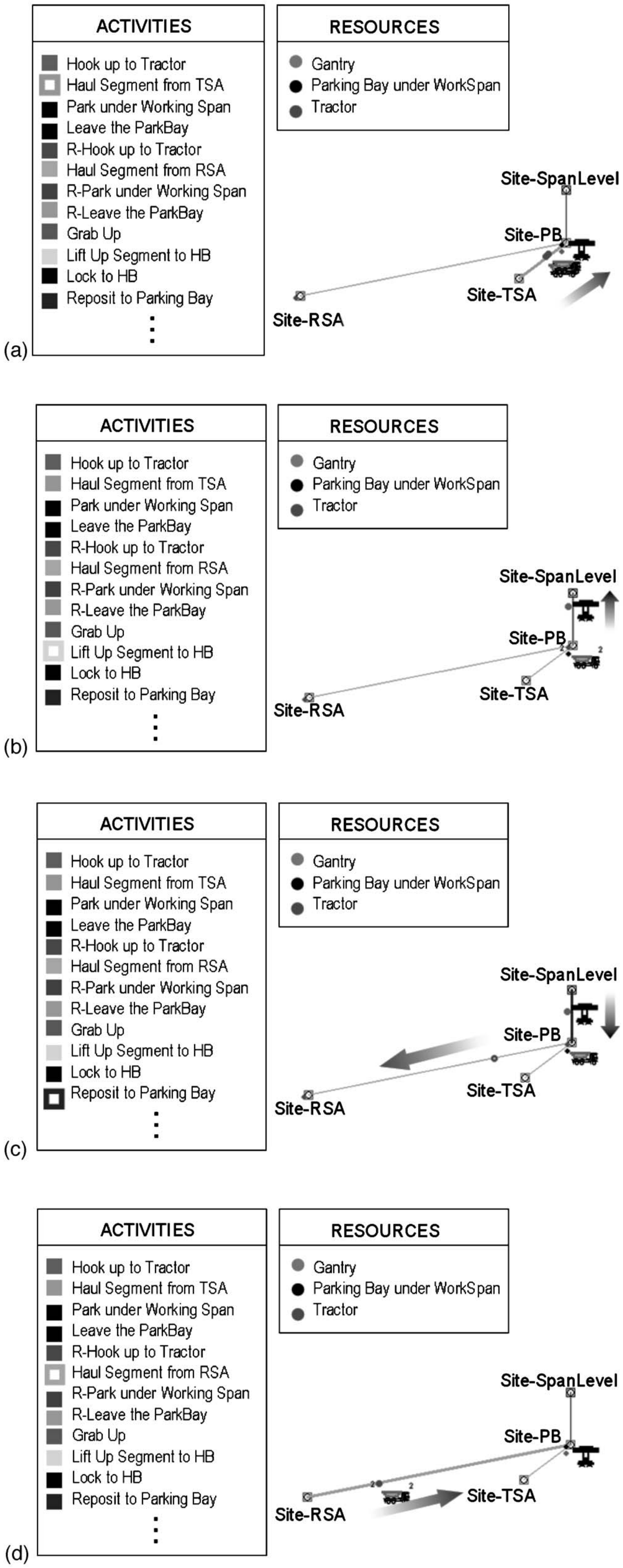

Fig. 9. Animation snapshots for the segment installation operations: (a) two tractors are hauling segments from temporary storage area to PB (b) spreader beam is lifting one segment; (c) one of the tractors is returning to remote storage area (RSA) while the spreader beam is being lowered; and (d) two tractors are hauling segments from RSA to PB

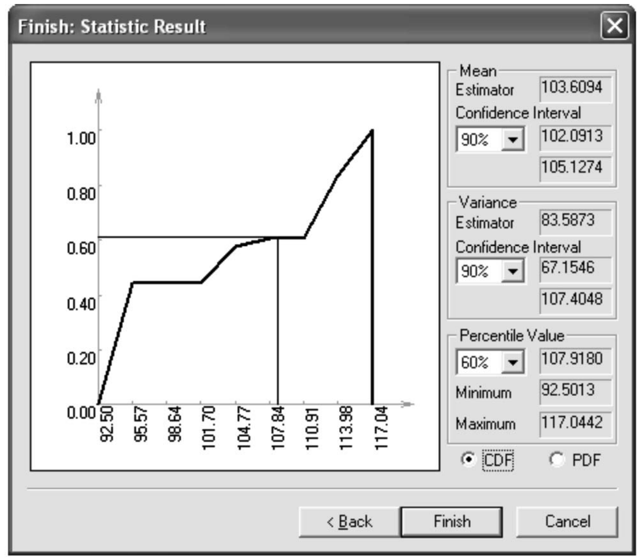

Fig. 10. CDF and statistical analysis of simulation outputs: total cycle time for erecting one span of viaduct

In the base-case scenario for simulation, input factors of the model were arranged to mirror the actual operations as observed during the site visit: 14 segments for one span were delivered in one batch at the night of Day 1 and all stored at the temporary storage area next to the working span; two tractors were rented, and the actual completion time for installing the span was before the lunch break on Day 5 (in other words, actual cycle duration was about four and one-half days).

First, segment installation processes being simulated were replayed through process animation based on a single run of the SDESA model (four animation snapshots are shown in Fig. 9). To further validate the simulation model, 100 Monte Carlo runs on the SDESA model were conducted, resulting in (1) the average total cycle duration of 103.61 hours—equivalent to 08:00 am in Day 5; and (2) the probability of completing the total cycle before the lunch break of Day 5 being about 60%—which was inferred from the cumulative distribution function (CDF) polygon for the total cycle time derived from simulation (Fig. 10). In brief, the SDESA model under the base case scenario was validated as a close parallel of actual site operations, providing a virtual basis for postulating and assessing alternative material inventory strategies, which is discussed next.

Simulation Experiment Design and Results

The objective of simulation experiment design was to evaluate the sensitivity of total cycle duration to various segment storage strategies, which are defined by (1) the number of segments stored at the remote storage area; (2) the transit time from the remote storage area to the working span; and (3) the number of tractors rented. A total of 17 scenarios were postulated and simulated.

The total cycle duration for each scenario was averaged from 100 Monte Carlo simulation runs, as listed in Table 1. As observed in the first 13 scenarios, given two tractors are available for hauling segments, the overall trend is that mean cycle duration prolongs either as the number of segments at the remote storage area increases or as the remote storage area is placed farther away from the site. In the case of Scenario 13, in which all 14 segments are assumed to be stored at the remote storage area with 45 min transit time, mean cycle time is extended to 116.61 h, which is

J. Constr. Eng. Manage., 2008, 134(4): 300-310

Table 1. Summary of Input and Output Factors for Simulation Experiments

Scenario	Rented tractors	Remotely stored segments	Tractor transit time	Mean cycle duration (h)
1	2	0	N/A	103.61
2	2	4	0.33 hr (20 min)	105.38
3	2	7		106.02
4	2	10		106.00
5	2	14		106.61
6	2	4	0.50 hr (30 min)	108.47
7	2	7		111.51
8	2	10		113.26
9	2	14		114.15
10	2	4	0.75 hr (45 min)	112.72
11	2	7		115.70
12	2	10		116.47
13	2	14		116.61
14	3	10	0.50 hr (30 min)	104.89
15	3	14		105.78
16	3	4	0.75 hr (45 min)	108.38
17	3	7		109.36

13 h longer than 103.61 h, resulting from the base case (note the base case is given in Scenario 1 in which all the segments are held in the temporary storage area).

To facilitate the visualization of the trend generalized from simulation results, a surface plot was developed for the 13 scenarios simulated (Fig. 11). The plot correlates mean cycle time with the number of segments remotely stored (denoted by the "SegNo.-T2" axis) and the transit time in minutes (denoted by the "Dist-T2" axis). It is observed from Fig. 11 that the slope against the "SegNo.-T2" dimension is not as steep as against the "Dist-T2" dimension, indicating the number of segments held in the remote storage area has a less significant impact on prolonging total cycle duration than the transit time. Additionally, an imaginary plane that intersects the surface plot at the total cycle time of 109 h (i.e., the end of lunch break on Day 5) can be taken as the threshold to distinguish feasible scenarios from infeasible ones: A dot beneath the threshold plane can be regarded as feasible.

Given three tractors available, it is inferred from simulation results that the remote storage area could be farther located from the working span (up to 30 min journey time on average) without considerably extending the target cycle duration. For instance, in Scenario 14, given ten segments were remotely stored, the transit time was 30 min, and three tractors used, the resultant total cycle duration would be 104.89 h.

The above simulation results were summed up in simple, straightforward terms and passed on to the project team of the participating contractor, as follows:

- When the temporary storage area near the working span is not sufficient to hold all 14 segments, the site manager is advised to locate a remote storage area within 25 min transit time (inclusive of any disruptions or delays caused by other ongoing site activities). Thus, the 4.5-day cycle time target would be achievable by renting two tractors, regardless of the number of segments stored at the remote storage area.
- In the case that the remote storage area is placed beyond 30 min transit time but below 45 min due to practical constraints, the site manager is recommended to consider two options: (1) Renting two tractors while limiting the number of segments stored at the remote storage area to under four; or (2) if more than four segments would be remotely stored, the site manager needs to rent three tractors.

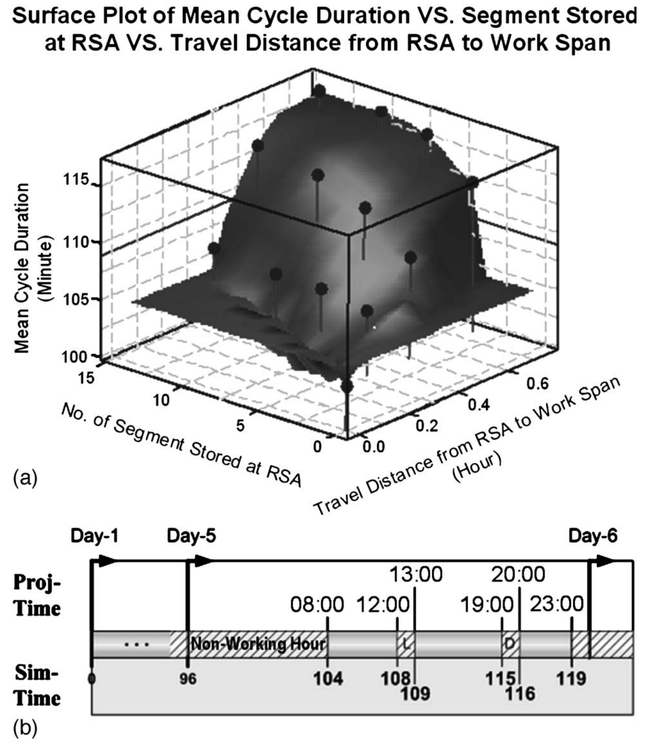

Fig. 11. (a) 3D-surface plot of mean total cycle duration (Mean Cyc. Dur.–T2) against the number of segments stored at RSA (SegNo.-T2) and transit time from RSA to working span (Dist-T2); (b) time line for converting continuous working hours into standard time format

Implementation and Site Feedback

By the end of July 2004, about 10% of viaduct spans had been completed. The simulation results were shared with the contractor's site team to provide decision support in constructing remaining spans. As informed by simulation analysis, the contractor stored part of the precast segments—remote from the working span yet within a distance threshold—to alleviate congestion at the construction site while maintaining smooth span installation operations and meeting the tight construction cycle time.

According to email correspondence from the contractor, "a yard (called Kanson yard) had been rented to store up to four spans of precast segments in order to cope with the working space congestion problem along many spans." The journey time by a loaded tractor from this remote storage area to most working spans involved was within 20 min, close to the 25 min threshold as determined from simulation. The precast inventory arrangement allowed the contractor to well control the targeted cycle duration and brought the project to timely completion in October 2005.

In November 2005, a review meeting was held to let the research team and a group of experienced and junior personnel of the participating contractor share experiences gained from the simulation research. In conclusion, through this university-industry joint endeavor, the research team convinced the project director, as well as field managers, of the functionality and effectiveness of operations simulation in assisting them in designing the materials handling system. With process flowchart, site layout

J. Constr. Eng. Manage., 2008, 134(4): 300-310

plan, and process animation produced in a view-centric simulation environment, it is straightforward to establish, validate, and communicate the operations simulation. With the aid of simulation, even junior engineers—with limited past experience—would be capable and confident to draw up an actionable construction plan that would lead to the enhancement of cost effectiveness and productivity in the field.

Conclusion

A construction site can be regarded as a materials handling system, the efficiency of which dictates whether productivity and economy objectives of the whole project can be attained. Nonetheless, the interactive, complicated system environment of a construction site renders conventional site layout planning and scheduling techniques to be inadequate in coping with materials handling system design in construction. At the meantime, the lack of an accepted practical technique for evaluating the efficiency of a chosen materials handling system design makes it difficult to choose objectively between possibilities.

In this research, we have presented a university-industry joint endeavor for improving the effectiveness of the materials handling system on a precast viaduct construction project by implementing the simplified discrete event simulation approach (SDESA.) How to apply the simulation methodology of SDESA is elaborated step by step, illustrated with the case study of designing, evaluating the materials handling system for a precast viaduct construction project in Hong Kong. Particular emphasis is placed on procedures of establishing a simulation model, validation of the simulation model, design of simulation experiments, and analysis of simulation results. The knowledge derived from simulation adds to experiences of site managers; as informed by the simulation analysis, the contractor stored part of the precast segments—away from the working span yet within a distance threshold—to alleviate congestion in the site space while maintaining the tight construction cycle time. The research team convinced the project director as well as field managers of the functionality and effectiveness of simulation in assisting them in designing the materials handling system. With the aid of simulation, even junior engineers would be capable and confident to draw up the best construction plan that would lead to the enhancement of cost effectiveness and productivity in the field.

Although considerable differences exist among projects, contractors, cultures, regions, and countries, technology underlying a typical, repetitive construction practice bears common traits and remains much neutral to design, social, legal, and cultural factors. Thus, it is advisable to apply simulation modeling to assess and review certain repetitive construction practices, aimed at continuous improvement.

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J. Constr. Eng. Manage., 2008, 134(4): 300-310