FORMALIZATION OF CONSTRUCTION OPERATIONS SIMULATION FRAMEWORK FOR MODELING LARGE CIVIL ENGINEERING PROJECTS FOR DECISION MAKING PURPOSES

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Formalization of Construction Operations Simulation Framework for Modeling Large Civil Engineering Projects for Decision Making Purposes

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CERTIFICATE OF ORIGINALITY

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__________________________ (Signed)

Lau Sze Chun (Name of student)

To my parents, Anita Cheung and Michael Lau,

my brother, Kenny Lau,

and my girlfriend, Grace Wong.

Abstract

Construction simulation provides a virtual platform on computer for design, analysis and experimentation of construction methods in order to offer better understanding and solutions. Despite the fact that computer simulation software has become user friendly to learn and apply and many real-world applications for aiding critical decision making have been demonstrated by simulation researchers, the industry generally has not yet been convinced with the advantages and the cost-effectiveness afforded by simulation. Most of the civil engineering projects are large, featuring extensive site-specific information, numerous practical constraints and convoluted logical sequences. Special-purpose simulation templates with default settings are regarded by the construction managers as being still too general to be directly applied to address their own problems. On the other hand, a general-purpose simulation platform demands the simulation knowledge and application skills of a simulation modeler who is generally trained at PhD level in Construction Engineering and Management. Neither a special-purpose nor a general-purpose simulation approach has yet to be widely implemented in practice.

This research formalized the methodologies to approach, structure and represent the reality in construction applications by proposing and implementing 1) a formalized framework for process mapping and simulation modelling and analysis, and 2) a

simplified discrete event simulation approach to apply combined modeling for simulating large civil engineering projects, which are predominantly discrete but include some plants or processes that are continuous in nature.

The formalized framework for computer simulation modeling were developed; following the procedures on how to establish a process mapping model bridges the gap between the reality and a simulation model. The detailed procedures were also presented and demonstrated with practical applications. The framework provides hands-on application guidance and reduces many subjective interpretations and assumptions that simulation modelers need to make when building simulation models. The resulting process mapping models can be rapidly converted into simulation models by applying the Simplified Discrete Event Simulation Approach (*SDESA*). The *SDESA* models precisely represent extensive construction operations in a straightforward manner and executing *SDESA* simulations lends effective decision support to construction managers at the construction operations planning stage in terms of use of resources use, cost and time.

In addition, special constraints in certain practical problems were identified to demand the use of advanced modeling methods (e.g. discrete-continuous combined modelling). This research has developed an approach for modeling a continuous plant by defining a finite quantity of discrete resource entities to represent a continuous component or process without considerable loss of model accuracy, while retaining the ease of applying discrete simulation modeling. The approach was demonstrated with a concrete pumping case in which a stationary pump system processes truckloads of concrete in continuous flows. A practical application of an iron ore processing plant in a mining site was used to validate the proposed framework and demonstrate its implementation.

The formal framework for process mapping and simulation modeling was applied to three large civil engineering projects of 1) an airport demolition project, 2) a microtunneling project, and 3) a mining project. The framework was capable of solving a wide range of construction applications and the resulting process mapping models were converted to simulation models on the *SDESA* computer platform where the simulation analyses were carried out. The production rate and resource utilization rates derived from simulation indicated a close match between the simulation model and the actual site system in all these case studies. The proposed approach adds to the usefulness and flexibility of a discrete simulation methodology in modeling complicated construction systems.

Publications Arising From the Thesis

Technical Papers in Refereed Journals

1. **Lau, S.C.**, Lu, M., and Poon, C.S. (2014). “Formalized Approach to Discretize a Continuous Plant in Construction Simulations.” *Journal of Construction Engineering and Management*.
2. Lu, M., **Lau, S. C.**, and Ariaratnam, S. (2009). “Discussion of “Productivity study of microtunneling pipe installation using simulation” by Roy Yu Luo and Mohammad Najafi.” *J. Infrastruct. Syst.*, 15(2), 133-135.
3. Lu, M., Lau, S.C., and Poon, C.S. (2009). “Simulation Approach to Evaluating Cost Efficiency of Selective Demolition Practices: Case of Hong Kong’s Kai Tak Airport Demolition.” *Journal of Construction Engineering and Management*, 135(6), 448-457.

Technical Papers in Refereed Proceedings

1. **Lau, S.C.**, Lu, M., Ariaratnam, S.T., *et al.* (2008), "Uncertain Factors and Performance Monitoring in Trenchless Construction Operations." *In: Ren, A, Ma, Z and Lu, X (Ed.) 12th International Conference on Computing in Civil and Building Engineering & 2008 International Conference on Information Technology in Construction*, 16-18 October 2008, Beijing, China, Tsinghua University Press, 265.
2. **Lau, S.C.**, Lu, M, Ariaratnam, S.T., *et al.* (2010). "Simulation-Based Approach to Planning Temporary Traffic Arrangement for Microtunneling Operations in Urban Areas." *10th International Conference on Construction Applications of Virtual Reality 2010*, 4-5 November 2010, Sendai, Miyagi, Japan, 395-404.
3. **Lau, S.C.**, Lu, M., and Lo, Y.K. (2010). "Planning Pipe-Jacking Operations Through Simulation Modeling Based on a Twin-Tunnel Microtunneling Site in Hong Kong." *Proceedings of International No-Dig 2010, 28th International Conference and Exhibition*, 8-10 November 2010, Singapore, 313-319.
4. **Lau, S.C.**, Lu, M., and Poon, C.S. (2011). "Integration of Construction and Traffic Engineering in Simulating Pipe-jacking Operations in Urban Areas." *Proceedings of the 2011 Winter Simulation Conference*, 11-14 December 2011, Phoenix, Arizona, 3516-3525.

5. **Lau, S.C.**, Lu, M., and Poon, C.S. (2013). "Modeling the Production Capacity of a Continuous Plant Using Discrete Event Simulation." *Proceedings of 2013 ASCE International Workshop on Computing in Civil Engineering*, 23-25 June 2013, Los Angeles, CA, USA, ASCE, 873-880.
6. Lu, M., **Lau, S.C.**, and Chan, K.Y. (2007), "Combined Simulation Modeling Using Simplified Discrete Event Simulation Approach – A Mining Case Study." *Proceedings of the 2007 Summer Computer Simulation Conference, the Society of Modeling and Simulation,* San Diego, CA, July 2007, 421-428.

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Chapter 1

Introduction

1.1 Problem Statement

Simulation modeling is a tool for formulating a logical model of a real world system on the computer medium with the aim of achieving a better understanding of the system and hence helping to resolve problems (Law and Kelton 2000). Various discrete event simulation methods and applications have been developed in the domain of construction engineering and management over the past decades, contributing to the culmination of much common knowledge and practice in this field.

For construction engineering, limited simulation applications were identified because use of simulation modeling to reflect large civil engineering projects in the real world is not easy. General-purpose simulation platforms such as *Cyclic Operation Network (CYCLONE)* (Halpin 1977) / *State and Resource Based Simulation of Construction Processes* (*STROBOSCOPE)* (Martinez 1996) require a simulation modeler being academic knowledgeable. *CYCLONE* simulation courses are generally taught at MSc level for applications. In some universities, *CYCLONE* is also taught at PhD level for system development, integration, optimization, methodology enhancement. The simulation modeler should also be experienced in relevant field to be a competent construction manager (who assumes the responsibilities of the field commander in chief). Special-purpose simulation templates have been developed in order to train a construction manager to be a simulation modeler as well (Hajjar and AbouRizk 2000). But construction managers usually find special-purpose simulation templates with pre-defined common settings still too general and not appropriate for immediate use to address their own problems. They generally lack of academic knowledge to modify the templates to reflect the site-specific information, practical constraints and logical sequences in the large civil engineering projects.

In view of the above, few applications are seen in the construct industry. Thus, there is an urgent need to providing a critical linkage to bridge the gap between the reality and the computer simulation model by formalizing the way to approach reality in construction applications. This research developed a framework for process mapping model and a straightforward combined modeling method in order to cope with modeling large civil engineering projects, which are predominantly discrete but contain limited components or processes that are continuous in nature. This would benefit both the construction manager and the simulation modeler to make simulation modeling applicable to field decision making and productivity improvement.

1.2 Research Objectives

The objectives of this research are to approach, structure and represent large civil engineering projects into simulation-friendly *process mapping models* by generalizing a formal framework for process mapping and ensuing simulation analysis. The academic contribution of the research is to introduce a process mapping model positioned between the reality and the computer simulation model, providing a critical linkage to bridge the gap between real world applications and computer simulation models and facilitate the communication between construction managers and simulation modelers. A formal framework means it can be applicable to virtually all the construction applications. The framework will formalize the way to model large civil engineering projects found in the real world. In the current practice, during the setup of process mapping models, some special constraints will be dealt with as exceptional modeling methods (like the continuous mining process). This implies that simulation modeling is still quite subjective and comprises large part of art; the research objective is to turn the part of art more into a kind of applied science or engineering methodology - for a given problem, following the proposed framework for process modeling and simulation analysis, two modelers would be expected to offer similar and comparable solutions in regards to the model itself and the final results, without making too many subjective interpretations and assumptions. This research will deal with the application of the formal framework in some particular real world problems. With the process mapping model established, a simulation model can be rapidly developed by applying the *Simplified Discrete Event Simulation Approach (SDESA)* simulation modeling platform, which was developed from previous in-house research (Lu et al. 2007a). The resulting *SDESA* model precisely represents various types of construction operations and provides a cost-effective basis to support critical decision making processes during construction planning in terms of use of resources, time and cost.

1.3 Formal Framework for Process Mapping Model of Complicated Problems

The knowledge gap between simulation researchers and practical engineers in relation to modeling application mainly revolves around problem definition and formulation. The practical contribution of the research is to bridge the gap through educating the engineers on how to look into and simplify complicated problems but without oversimplifying them, and how to communicate effectively for simulation modeling and analysis. The research is not intended to train people to program or apply a particular simulation tool. Instead, the proposed formal framework can assist in the formulation of simulation-friendly *process mapping models* independent of particular simulation tools. The process mapping models can be readily convertible into simulation models by use of commonly available simulation tools, including but not limited to *CYCLONE*, *Arena*, or even direct coding. In this thesis, the *SDESA* computer platform only provides one convenient means to showcase the application of the framework and prove the concept through conducting practical case studies based on 1) an airport demolition project, 2) a microtunneling project, and 3) a mining project. A formal framework of process mapping and simulation modeling and analysis is developed to represent various types of construction activities accurately and efficiently.

1.4 Framework for Continuous Plant Modeling

Apart from the abovementioned framework for process mapping of complicated problems which are discrete (or predominately discrete) in nature, another contribution of this research is to develop a framework for modeling a continuous plant by applying discrete events or resources. The potential loopholes in modeling a plant in continuous nature by simplifying it as one discrete resource entity are clarified and illustrated with a concrete pump example. An approximate method for representing a continuous plant by a finite quantity of discrete resource entities *(N)* so as to ensure the accuracy of the model as desired, whereas retaining the ease of applying discrete simulation modeling is formalized. This framework will be implemented to model iron ore segregation process in a mining case.

1.5 Dissertation Outline

This thesis is organized as follows: literatures on discrete event simulation are reviewed in Chapter 2; the formalized framework for process mapping and simulation modeling and analysis will be proposed in Chapter 3; the computer application of the framework of an airport demolition project and a microtunneling project will be demonstrated in Chapter 4 and Chapter 5 respectively; the framework for continuous plant modeling by use of a finite quantity of discrete resources will be presented in Chapter 6 and the application of an iron ore process modeling demonstrated based on a mining project in Chapter 7. Conclusions and discussions will be given in Chapter 8.

Chapter 2

Literature Review

2.1 Construction Simulation

The simplicity and computerization of the critical path method (CPM) has led to its wide adoption in construction project planning. Nonetheless, it is difficult and inadequate to use CPM to address resource availability constraints, space scheduling and site layout planning, dynamic work flows, and repetitive units of construction in the context of operations planning for construction crews (including labourers and equipment) in the field.

On the other hand, the simulation methodology of activity cycle diagrams (ACD) lends itself well to modeling construction operations. Simulation keeps track of the changes of the state of a system occurring at discrete points of time (Pidd 1998) and builds a logical model of a system for experimenting on a computer (Pritsker 1986). With the modeling capabilities and usability being continually enhanced, ACD-based construction simulation tools have evolved from the original *CYCLONE* methodology (Halpin 1977, Halpin and Riggs 1992) to the programmable *STROBOSCOPE* (Martinez 1996).

2.2 BIM (Building Information Modeling)-enabled Construction Simulations

Building information modeling (BIM) provides a three-dimensional (3D) representation of a centralized database containing design related information of a facility. BIM is increasingly being embraced by architectural and structural designers to support design, drafting and communications. BIM has also been coupled with structural analysis and project scheduling analysis (Chan and Lu 2012) and holds the potential to be the game-changer technology for the entire architecture, engineering, and construction industry. Despite all the advances, mainstream BIM solutions still fall short of serving practical needs of the constructor, being a contractor, a subcontractor or a field crew; as such, BIM is rarely applied to lend critical decision to detailed estimating, detailed job planning, and execution control on a construction project. A quick overview of advances in BIM technologies along with a critical review of BIM applications is presented. This leads to identification of main challenges that still prevent the constructor from adopting BIM and implementing integrated project delivery (IPD).

2.2.1 BIM-based Scheduling

In terms of scheduling, research efforts in the last decade have evolved from traditional 3D Computer-aided design (CAD) model supported critical path scheduling (De Vries and Harink 2007) to BIM model with enriched information seamlessly linked with a scheduling platform (such as Primavera P6) (Liu et al. 2014).

De Vries and Harink (2007) proposed a construction algorithm to generate a construction plan from a 3D CAD model, considering topology/geometry of building components in sequencing construction activities, whereas largely ignoring engineering details relevant to design and construction. Kataoka (2008) subsequently presented an approach to generate a construction schedule from simple 3D building geometries and a predefined construction method, which is intended to be used at the very early stages of projects before the structural system of the project is specified. Kim et al. (2013) established a prototype for automating the generation of construction schedules using open BIM technology. Their work has focused primarily on automating data extraction from a BIM file stored in an industry foundation classes (IFC) format and parsing building information as the inputs for scheduling, without addressing sequencing rules applied by crews in the field. Moon et al. (2013) studied a BIM-based construction scheduling method using the optimization theory with the objective of reducing activity overlaps, but their main focus with respect to BIM is limited to visualization instead of BIM-based scheduling or estimating. Construction schedule resulting from BIM related research can be largely categorized as the “design-centric product component” level, instead of the “construction-centric operation activity” level.

The detailed resource schedule generated from operations simulation has been increasingly utilized. For instance, Wang et al. (2014) developed a BIM interface system to generate the on-site operation level schedule. Yet, their research was limited to reinforced concrete construction and did not provide flexibility in considering different construction methods.

2.3 Discrete Event Simulation

Discrete event simulation differs from continuous simulation with respect to the mechanism by which the state of the system changes over time (Prisker and O'Reiley 1999). In discrete event simulation, the modeler concerns about the logical conditions for triggering the occurrence of events that change the system state only at discrete points in time. In contrast, in continuous simulation, the state variables of the system are assumed to change continuously with time; and a set of differential equations are developed to portray the behaviour of the system. Actually, the two simulation viewpoints can be interchangeable in addressing many real world applications. The primary determinant of the modeling viewpoint being applied on a particular problem is the education background of individual modelers (Prisker and O'Relley 1999). For instance, electrical, mechanical, chemical engineers and physicists tend to be continuous modelers, whereas operations researchers and industrial engineers basically are discrete simulation modelers.

Driven by construction technology and resource availability, construction system modeling entails mapping the processes in regards to transit, matching and engagement of manpower (labourers) and machinery (equipment) resources on certain activities occurring at certain site locations (Lu et al. 2007a). For its simplicity, most of the work in construction simulation falls into the "discrete" classification (Shi and AbouRizk 1998). Therefore, discrete event simulation provides the norm viewpoint for the representation of a construction operations system into a simulation model. *CYCLONE,* along with its extensions and add-ons, has remained to be the best-known discrete simulation method used in construction engineering research.

Nonetheless, certain elements that are continuous in nature - being resources or processes - exist within a predominantly discrete construction system. Modeling such systems involves both discrete and continuous simulations, resulting in the hybrid viewpoint of combined simulation (Law and Kelton 2000). In the construction domain, a plant of continuous nature often constitutes the leading resource in a site production system, driving the configuration of supporting resources and controlling the overall productivity performance. Let us consider the case of a concrete pump equipped with a feeder container and pipeline, which continuously transfers concrete from the mixer truck unloading point to the placing point situated on the floor being built. In this case, the concrete supply rate and the concreting crew's productivity need to be synchronized with the production rate of the pump. Relevant examples also include 1) an aggregate production plant with a conveyor system to process truck loads of raw material into aggregates of various sizes in continuous flows; 2) an iron ore processing plant with magnetic separator drums for extracting iron sand from the slurry of iron ore. Nevertheless, it is worth mentioning that the complexities inherent in applying combined simulation modeling would hamper its use by practitioners to improve their day-by-day work practices. In spite of enhancements to project planning in sophistication and accuracy, a combined simulation approach in general incurs the expense of additional time spent developing a detailed model (AbouRizk and Wales 1997). Construction modelers prefer a more convenient alternative to simulating the production capacity of the continuous plant, which essentially "discretizes" the modeling of continuous elements in a predominantly discrete system without loss of significance or accuracy. As such, a direct application of a discrete simulation method (such as *CYCLONE*) would afford the straightforward modeling solution to the whole site system.

Substantial research has been undertaken into bridging the gap between research and application in construction simulation by simplifying simulation methodologies, whereas retaining its modeling functionalities. Representative developments include: 1) the resource-based approaches, which generate full-scale and large simulation models through linking atomic models for particular resource operating processes (Shi and AbouRizk 1998) or preprogrammed construction resources (Oloufa et al. 1998); 2) the 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) the 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 1996; Hajjar and AbouRizk 1998; Hajjar et al. 1998; Martinez 1998; Hajjar and AbouRizk 2000; Hajjar et al. 2000; Mohamad and AbouRizk 2005; Song and AbouRizk 2006). AbouRizk (2010) presented an outline of advancements in construction simulation theory throughout the past decades.

CYCLONE uses the basic modeling elements of Queue node and Combi node to represent productive/non-productive states of resource entities and portray their dynamic interaction and flow within a construction system. Fundamentally, *CYCLONE* is a typical activity-scanning (AS) approach to discrete system simulation (Martinez 1996). To form an AS model, the modeler follows a formal modeling procedure: 1) identifying activities in the system; 2) listing the start-up conditions for each activity; 3) drawing activities in blocks (called "Combi" activity nodes in *CYCLONE*) and conditions in circle shapes (called "Queue" nodes in *CYCLONE*); 4) linking activity blocks and condition circles according to the construction logic; and 5) initializing the system by assigning simulation entities (or called tokens, representing the initial system state) to condition circles. The symbols or modeling elements of *CYCLONE* are designed to be simple and straightforward for developing schematic representations of construction operations. Thus, *CYCLONE* facilitates the communication of complicated construction processes with flowchart-based conceptual model, and provides an intermediate medium to convert the conceptual model into the digital model. As the inception of *CYCLONE*, much enrichment based on the blueprint of *CYCLONE* has been proposed to extend its merits, such as *INSIGHT: Interactive Simulation of Construction Operations Using Graphical Techniques* (Kalk 1980; Paulson et al. 1987), *RESQUE: A Resource Oriented Simulation System for Multiple Resource Constrained Processes* (Chang and Carr 1987), *MicroCYCLONE* (Lluch and Halpin 1982; Halpin1990), *UM-Cyclone* (Ioannou 1988), *DISCO: Dynamic Interface Simulation for Construction Operations* (Huang and Halpin 1993), *ABC: Activity-Based Construction*

(Shi 1999), *Web CYCLONE* (Halpin et al. 2003), *HK-CONSIM: A Practical Simulation Solution to Planning Concrete Plant Operations in Hong Kong* (Lu et al. 2003). The most recent "offspring" of *CYCLONE* is *STROBOSCOPE: State and Resource Based Simulation of Construction Processes* (Martinez and Ioannou 1994, Martinez 1996), which makes *CYCLONE* programmable and extensible so as to tackle the simulation of large civil engineering projects. Object-oriented discrete-event simulation systems were then developed and applied including Liu and Ioannou (1992), *CIPROS* (Odeh et al. 1992), Shewchuk and Chang (1991), Oloufa (1993) and Martinez (1998). AbouRizk and Hajjar (1998) introduced the *Simphony* as a simulation language for general-purpose modeling and AbouRizk et al. (1999) and AbouRizk and Mohamed (2000) further developed *Simphony* for special purpose simulation uses.

Discrete-event simulation keeps track of the changes of the state of a system occurring at discrete points in time and builds a logical model of the system for experimenting with it on a computer (Prisker 1986). Simulation of construction operations 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 et al. 1993). The modeling capabilities and ease of use of simulation tools have been enhanced from the original *CYCLONE* (Halpin 1977) to the more recent development of *STROBOSCOPE* featuring programmability and extensibility (Martinez 1996). Marzouk et al. (2010) developed a tool for planning microtunnels projects using computer simulation. Visual Basic 6.0 was used as input module for the construction planners (users) and *STROBOSCOPE* simulation was adopted for the shaft and microtunneling construction. Three types of shaft construction and three types of microtunneling construction were simulated and evaluated in terms of the cost and time simulation. In recent years, vision-based technologies have been applied to simplify the input data collection for simulation modeling. Examples include: Rezazadeh Azar and McCabe (2012) developed an automated visual recognition of dump trucks by analysis of construction videos. Rezazadeh Azar et al. (2013) further provided a framework so-called server-customer interaction tracker (SCIT) through integration of several cutting-edge computer vision algorithms, spatiotemporal information and background knowledge to detect and count the dirt loading cycles from site videos.

2.4 *Cyclic Operation Network (CYCLONE)*

The process mapping technique of Activity Cycle Diagram (ACD) relies on the alternate use of circle and square nodes to depict the passive and active states of resources in dynamic, resource-driven work flows. ACD underlies *CYCLONE*, which is the most widely employed simulation methodology in construction research. *CYCLONE* uses a small set of basic modeling elements to map resource-driven construction processes (Figure 2.1).

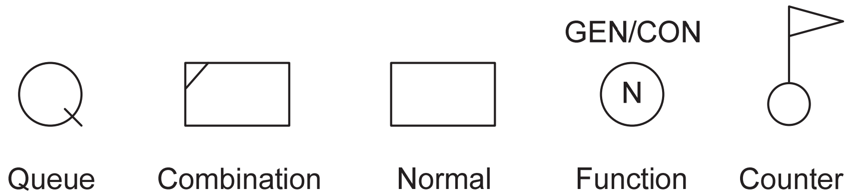


Figure 2.1. Basic Modeling Elements of *CYCLONE*

In a *CYCLONE* model, a grouping of "Que" nodes (a circle with a slash at its lower right corner) and "Combi" nodes (a rectangle with a slash at the upper left-hand corner) are used to trace the active and idle states of construction resources that are engaged in various activities. A "Combi" node represents a constrained activity and is preceded by at least two "Que" nodes. That means at least two types of resources need to be available before they are engaged in executing one activity. An unconstrained activity is called a "Normal" activity and symbolized with a simple rectangular node in *CYCLONE*. Additionally, function nodes − circles tagged with *"CON N"* or *"GEN N"* in *CYCLONE*− serve for consolidating or generating resource entities by the quantity of *"N"*, so as to enable complex logical linkage between different work flows.

2.5 *Simplified Discrete Event Simulation Approach (SDESA)*

Simulating a construction system by the simplified discrete event simulation approach (*SDESA*) (Lu 2003; Lu and Wong 2007) entails 1) delineating major work flows, 2) defining activities within each work flow along with flow entities associated with each work flow, and 3) identifying resource entities involved in the system. The basic modeling elements of *SDESA* are flow entity diamonds and activity blocks (shown in Figure 2.2). A flow entity diamond precedes a series of activities to initialize the amount of work units (flow entities) to be handled. An activity block represents a task that consumes time and resources in processing flow entities. Reusable resources (manpower, machinery, and work space) are limited in availability and initialized in the resource pool. The reusable resources required to perform an activity are marked on the top left corner of a related activity block. Upon finishing an activity, those resources to be released to the resource pool are marked on the top right corner [e.g. in Figure 2.2 (a), one loader (LD) is required for loading a dump truck and released upon finishing “Load Granular” activity].

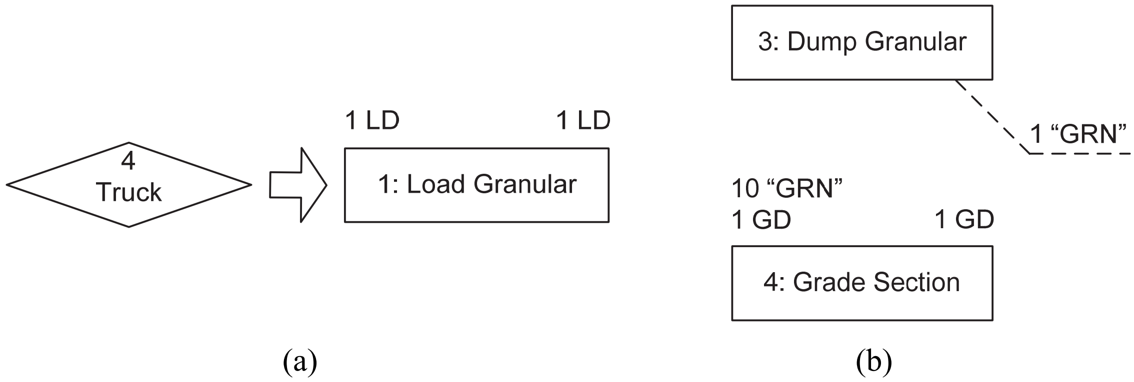


Figure 2.2. Basic Modeling Elements of *SDESA*

By contrast, disposable resources are either intermediate products or information units generated by one activity (marked to the bottom right corner of activity block) and required by another (shown on the top left corner of the relevant activity block). For instance, in Figure 2.2 (b), the disposable resource "GRN" denotes one truck load of granular aggregates and is generated at the end of the "Dump Granular" activity; 10 "GRN" and 1 grader constitute the resources required for grading one road section (i.e. "Grading Section" activity). Note that disposable resources also provide an effective means to establish the interdependent relationships between various activities/processes in *SDESA*.

In addition, in order to effectively model resources' transit among various activity locations in the site system, Lu et al. (2007) enhanced the algorithm formation and model structure of *SDESA* by adding two additional objects to the *SDESA* model definition. One is called "Location Set", which contains definition of main locations in the site system (such as location's ID, and its centre coordinates); the other is called "Resource Transit Information System", which includes transit duration definitions for particular resources to move from one location to another.

To sum it up, a *SDESA* model consists of 1) a process flow chart describing jobs (flow entities), activities, precedence relationships, resource requirements (reusable and disposable), and other logical constraints, 2) a resource pool holding all resource entities provided, and 3) a resource transit information system for modeling any additional state changes (spatial and temporal) of the system due to a resource's transit between activity locations.

Various simulation applications have addressed different engineering problems including precast viaduct construction (Chan and Lu 2005) and sports facilities construction (Chan et al. 2007).

Shen et al. (2004) developed a mapping approach to examining the waste management on the construction sites. However, this mapping approach focused on the activities and the resources and failed to link the site layout with the operations processes.

Lu et al. (2006) enhanced Shen's (2004) mapping model by defining dotted arrows to portray inter-process dependencies and discretizing the space of a site system into key locations where processing activities occur, and the start and finish locations of each activity were further linked to the processing activity. Through these enhancements, the mapping model clearly presented the state changes of wastes and a facilitating resource over the site space; and the interdependent relationships between concurring processes. Yet, it is still challenging to formulate the mapping or simulation models for large civil engineering projects.

Lu et al. (2007A) developed a simplified process mapping procedure to facilitate *SDESA* model development which is formalized and generalized in this research. To initiate the mapping process, locations and boundaries of the site should be defined before performing the work breakdown. The work flows and their components, including the locations of activities and the resources required to execute the activities which are either fixed at a location or mobilized between two different locations, are identified. Finally, disposable resources in the form of intermediate material units are defined to map out the technological relationships among activities.

Chapter 3

A Formal Framework for Process Mapping and Simulation Modeling

3.1 Introduction

This chapter describes a formal framework for process mapping and simulation modeling. This chapter proposes the framework of the construction simulation approach and process mapping model in Chapter 3.2 and 3.3. Details of process mapping model are described in Chapter 3.4. The terminologies for simulation modeling by *SDESA* are defined in Chapter 3.5. Procedures to establish a process mapping model in simulating typical construction operations are given in Chapter 3.6, illustrated with a simple example. The process mapping models of cases for two real world projects in Hong Kong, namely, Kai Tak Airport demolition project and So Kwun Wat microtunneling project plus for a mining project in Indonesia are demonstrated in Chapter 3.7, 3.8 and 3.9 accordingly. Conclusions are drawn in Chapter 3.10.

3.2 Formal Framework of Construction Simulation Approach

The aim of particular construction simulation modeling is to achieve a better understanding of the problem and hence resolving it. General problems in construction planning include determining the likelihood of completion of the construction project on time and optimizing resource allocations, material delivery cycles and site layout.

The general simulation modeling approach is shown in Figure 3.1. At the planning stage, simulation tools are used to investigate the effects of various combinations of resource allocations, material delivery and site layout designs.

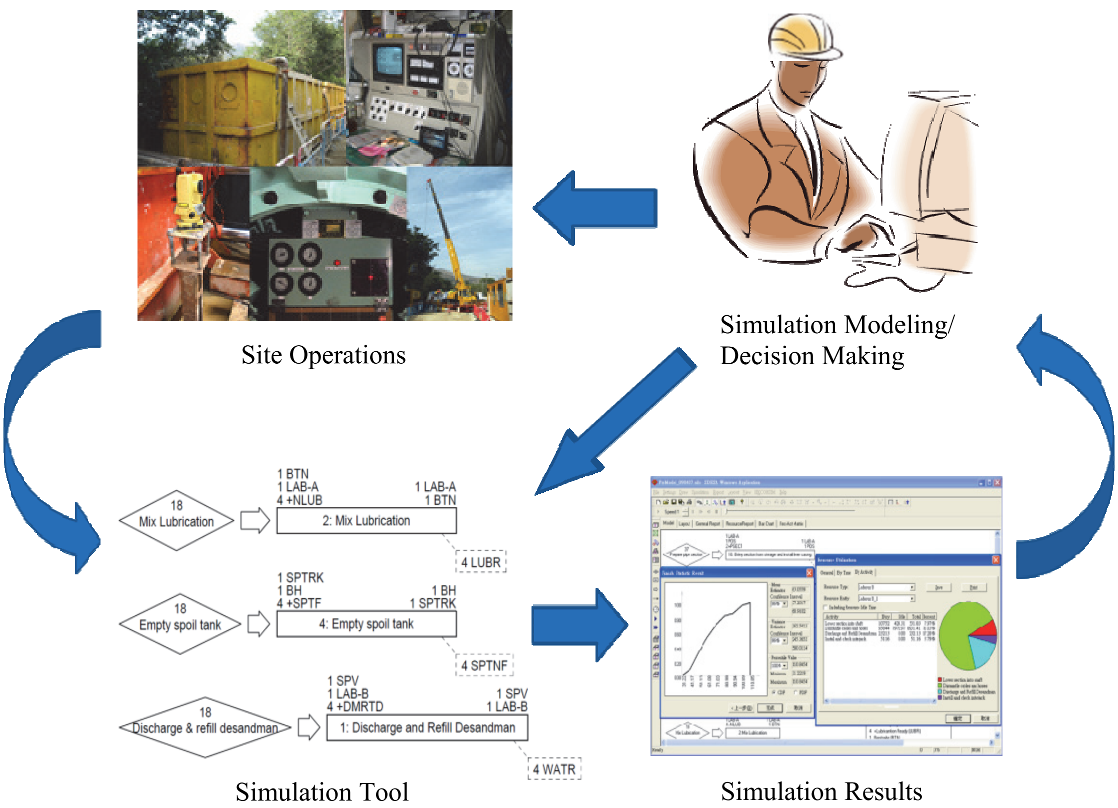


Figure 3.1. General Simulation Modeling Approach

The statistical distributions of the cycle times provide inputs to obtain system-level performances by executing valid simulation models in detailed jobsite planning. Before the project commences, the site planners can establish a simulation model for the preliminary estimation on the rate of construction, and the resources quantities required to complete the construction work within an anticipated completion date.

For any similar projects, the project planner can start from a typical simulation model template as a quick launch of simulation modeling. The simulation model is then fine-tuned based on the actual site layout plan and estimated activity durations. Further site constraints are defined in the model. Spatial constraints could be introduced according to the maximum quantity of materials to be stored on-site. This would further pose a logistical constraint to achieve just-in-time material deliveries.

Further simulation updating is necessary to assisting the construction planner in continuously revising the tentative completion date based on site information gathered. Once the model inputs are updated, the simulation experiments are conducted again to determine the remaining project duration and allocate the resources in order to optimize the utilization of resources and realize just-in-time material deliveries. During the construction stage, data from the field operations are collected for refining the accuracy of production rate prediction and project duration estimate. Distributions of the productive time and non-productive time are observed from simulation experiments for improving site management. Activity durations and utilization rates of various resources are produced as statistical outputs from the simulation model. With the assistance by simulation tools, the logistics management system and the operations management system can be optimized, maximizing the efficiencies in terms of time and resource use. Additional productivity analysis can be performed to determine the overall efficiency of site operations. The site operations model consists of logical sequences, activity durations and resource allocation which are defined during the site planning stage. In accordance with field operation processes, the main work flow along with supporting work flows are defined in the model.

3.3 Formal Framework for Process Mapping

The framework to establish a process mapping model in terms of work flow identification and site process representation for large civil engineering projects is defined and illustrated in Figure 3.2.

Simulation objectives and the scope of process mapping are first defined to confine the problem definition and avoid any wastage of modeling effort and computing power.

Input modeling comprises of an outline of site layout and key locations, collection of operation data, project information and specification of model assumptions.

Model establishment starts with the determination of flow entities including job entities and moving resources. Corresponding activities in each work flow are determined and combined with the work flows. Facilitating resources required by and released from activities are specified, intermediate products and signals, which as generated from activities and used to logically link up different work flows, are added as disposable resource entities.

The process mapping model is then validated against site observations and records or judgement by experts. Once the model is validated, it can be refined to include more advanced logical and operational details and further reviewed to examine if some non-core processes or details can be further omitted without compromising modeling accuracy. Stochastic distributions of activity durations, along with probabilities and duration distributions defining potential activity interruptions and resource breakdowns, should also be included.

The process mapping model is positioned between the reality and the computer simulation model, providing a critical linkage to bridge real-world applications and computer simulation models. The established process mapping model provides effective guidance to produce a computer simulation model by use of commonly used simulation tools.

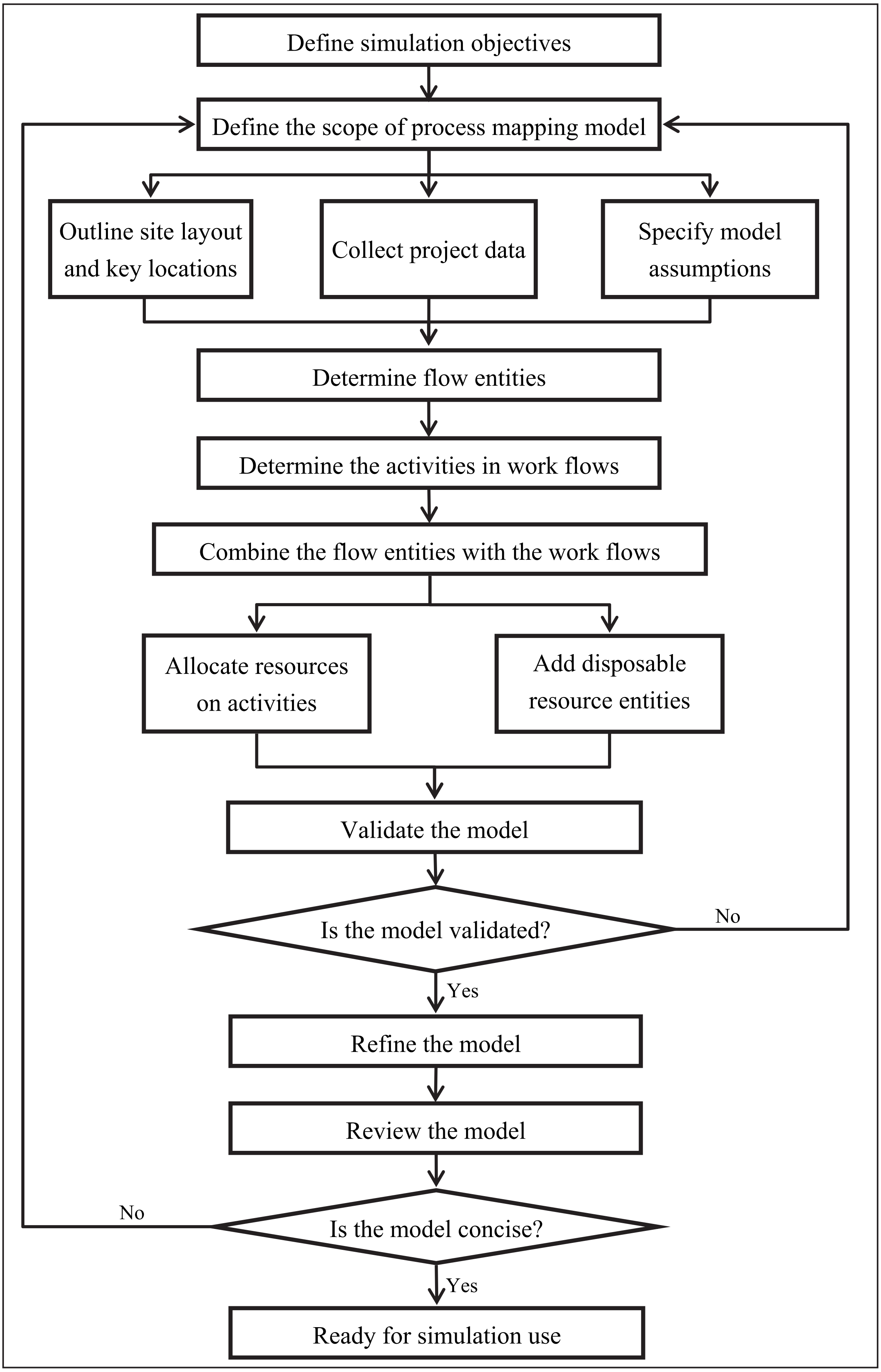


Figure 3.2. Formal Framework of the Construction Simulation Modeling Method

3.4 Procedures to Establish a Process Mapping Model

Procedures to establish a process mapping model as shown in Figure 3.2 are described below:

1. Define simulation objectives
2. Define the scope of process mapping model
3. Collect project data
4. Outline site layout and key locations
5. Specify model assumptions
6. Determine flow entities
7. Determine the activities in work flows
8. Combine the flow entities with the work flows (activity chains)
9. Allocate resources on activities
10. Add disposable resource entities
11. Validate the model
12. Refine the model
13. Review the model

Particularly, advanced settings of the *SDESA* simulation platform in connection with turning the process mapping model into the operation model on large civil engineering projects are also given so as to demonstrate the flexibility of the modeling framework to suit different site conditions.

1. Define Simulation Objectives

The framework for establish process mapping model begins with the definition of simulation objectives. Depending on the area of interest, some typical simulation objectives are listed in Table 3.1.

Table 3.1. Typical Simulation Objectives

Area of Interest	**Simulation Objectives**
Project programme	Project programme prediction
System optimization with flexible resources	Identification of bottlenecks in a project
System optimization with fixed resources	Optimize resource utilization rates
Evaluate the cost efficiency	Scenario analysis

2. Define the Scope of Process Mapping Model

The scope of a process mapping model refers to the spatial and temporal boundaries of the model in connection with the simulation problem. The model scope is defined to simplify the model by eliminating any unnecessary information so that modeling efforts and computing resources can be reduced during the system optimization and scenario analysis. For the time boundary, the whole construction project can be modeled as a definite scope of work flows each processing repetitive jobs of limited quantity.

However, computer requirement imposes a limitation to the time boundary so that the simulation model has to be scaled down to a controllable size for the subsequent system optimization and scenario analysis. Alternatively, only part of the construction project or a defined period may be modeled if the project lasts for a very long time with recurrent activities from time to time without significant change of site activities or geographical locations. The schematic diagram for defining the scope of the simulation model is shown in Figure 3.3.

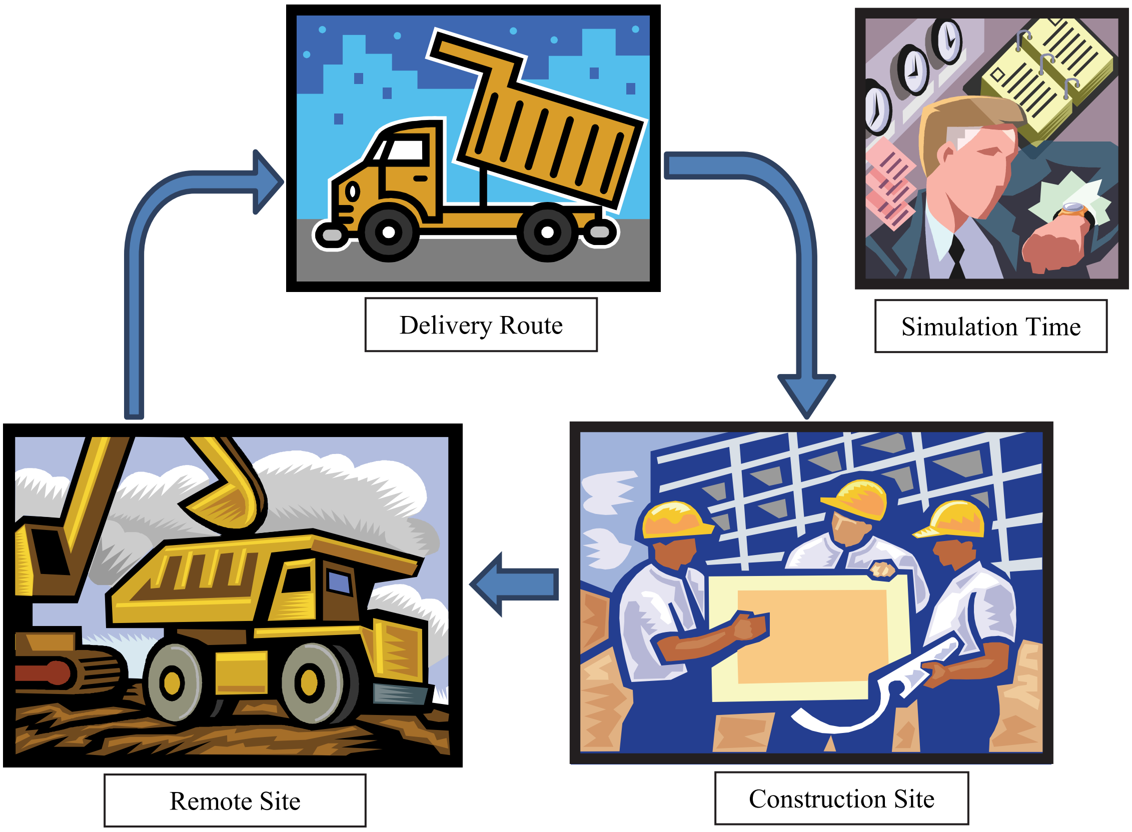


Figure 3.3. Define the Scope of Simulation Model

3. Collect Project Data

Project information can be collected based on the first-hand observation and information obtained from the site, or interview with competent construction managers. Information includes tasks to be completed or products to be delivered, site locations, activities, resources, working sequences, and operation time of the project. Supporting documents include the site layout plan, working drawings, method statement, construction sequence drawings, site diary and photos.

4. Outline Site Layout and Key Locations

The geographical coordinates of site operation locations, where the raw materials, intermediate products and final products will be transferred (from one location to another) or processed (at one location), are defined. Location circles are defined where individual activities will be carried out at that particular location or transited between two locations. Based on the geographical coordinates of key locations, the transit activity duration for transit between two locations can be determined by dividing the distance between two locations by the traveling speed. With insufficient traffic information, the traveling speed can be defined by approximating an average value or a uniform distribution. With sufficient information about the road condition and traffic flow characteristics, different statistical distributions on the traveling speed and thus the traveling time can be fitted for a particular transit activity. The site layout can be defined based on the site layout drawings and site photos.

5. Specify Model Assumptions

Based on the specific site information, assumptions on the status of working conditions, time, space, resources and volumetric changes are reasonably made in establishing the process mapping model.

Given the practical problems being addressed in this thesis, some common assumptions on the status of working conditions are described as below:

- All the machinery, trucks, workforce, and power supply should be in good condition to avoid causing any disruptions during the operation cycle. Otherwise, any interruption to all activities or individual ones can be defined based on the probability of event occurrence and the duration.

- Weather and temperature were consistently fine and suitable for work.

Some general assumptions on space are described as below.

- Spatial constraints were defined for site stockpiling capacity, truck delivery capacity and machine processing capacity.

Some general assumptions on resources are described as below.

- The resources can be shared among the activities.

- Standby resources would be necessary to ensure the continuous site operations. Otherwise, the probability and duration of resource breakdowns can be defined in the resource attributes. An example is the resource type setting for an old loader with a breakdown probability of ten per cent. The breakdown period is defined as beta distribution.

- Regular machinery maintenance could be defined in the model to ensure the working condition was always good.

6. Determine the Flow Entity

There are two basic types of work flows, namely *production line type work flow* and *vehicle loop type work flow*.

Production Line Type Work Flow

For production line *(PL)* type work flow, quantitative measurements should be carried out to calculate the total number of work units to be processed. Flow entity can be either a certain amount of work to be carried out or material units to be produced. It describes how many times each activity along the work flow will be carried out. Normally, this type of work flows does not involve cyclic transit activities between Location A and Location B.

An Illustration Example

The sieving work flow at the sieving area of Kai Tak Airport demolition project is shown in Figure 3.4.

Figure 3.4. Sieving Area at Kai Tak Airport Demolition Project

The *Sorted Broken Concrete (S_BC)* at the sieving area of Kai Tak Demolition site is to be transferred by a backhoe *"1 BH_SV"* to a screening plant where it would be sieved to *Small Broken Concrete "SBC"* of nominal sizes ranging from 0-200 mm (for those *S_BC* passing through the screen) and *Large Broken Concrete "LBC"* of nominal sizes ranging from 200-400 mm (for the *S_BC* rolling along the screen down to the ground). The *Sieve* work flow is a production line type work flow as represented in Figure 3.5.

For 900 units of *S_BC* to be processed with the sieve with a capacity of 5 units of *S_BC* per work unit, quantity take-off for the number of flow entity *"Sieve BC into SBC/ LBC"* can be determined by dividing 900 units of *SBC* by 5 units of *SBC* per work unit, i.e. 900 / 5 = 180 work flows.

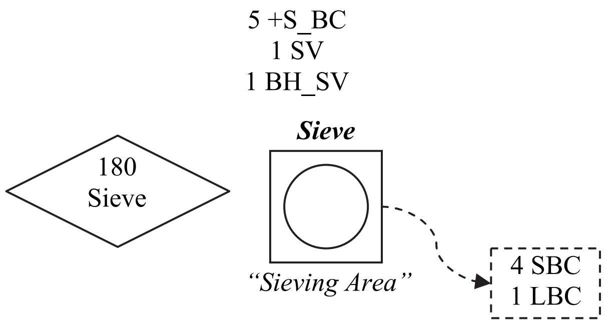


Figure 3.5. Process Mapping Model – Sieving Work Flow

Vehicle Loop Type Work Flow

For vehicle loop *(VL)* type work flow, the number of work units represents the amount of available *Moving Resources (MR's)*. Normally, it involves a *MR* moving around from point to point to match *FR* to generate *DR*. The activity cycle within the work flow processes in turns continuously. The definition of *Moving Resources* will be discussed in Procedure 9 below.

An Illustration Example

The steel recycling work flow in the Kai Tak Airport demolition project is given in Figure 3.6. The work flow type Upon the *Stockpiled Steel* "*SP_STL*" accumulated reaching 25 units, the contractor would notice the steel recyclers to collect the "*SP_STL"*. The Recycler would then send a truck "*R_TRK*" to collect the "*SP_STL"*, a *flagman* "1 *FM*" would lead the truck to the "*Steel Stockpiling Area*" where the "*SP_STL"* was loaded by a backhoe "1 *BH_G*". The truck would leave the site and await the signal for another cycle. The "*1 R_TRK*" denotes the maximum number of trucks concurrently available.

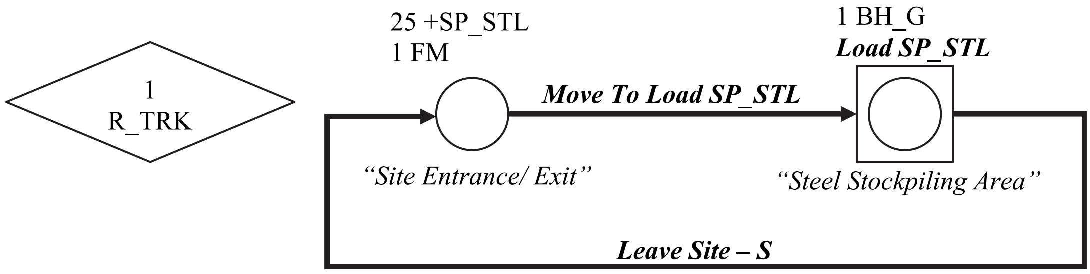


Figure 3.6. Process Mapping Model – Steel Recycling Work Flow

Interchangeability of Production Line Type and Vehicle Loop Type Work Flows

Under certain complicated circumstances, *PL* type and *VL* type work flows can be interchanged by means of alternative modeling techniques.

A *PL* type work flow can be transformed into a *VL* one by introducing a dummy activity looping back. Figure 3.7 shows an example of converting the *PL* type work flow as shown in Figure 3.5 into a *VL* type work flow by adding a dumping activity to create a return path to the starting point of work flow.

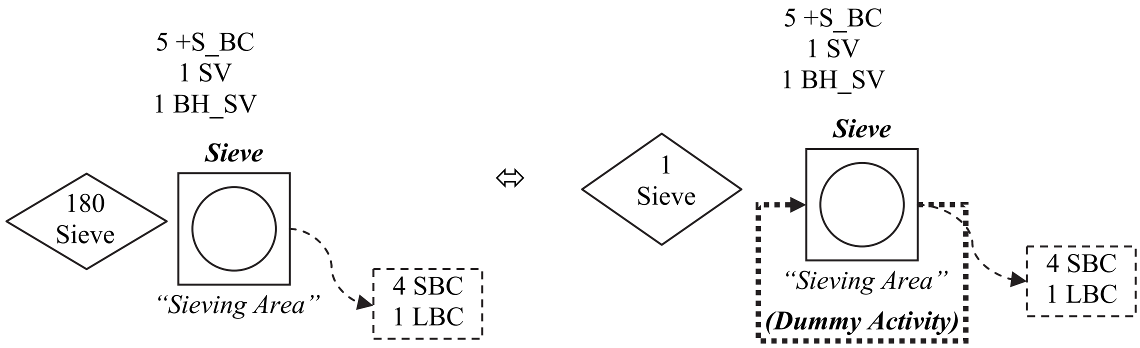


Figure 3.7. Conversion of a *PL* Type Work Flow into a *VL* Type Work Flow

On the other hand, a *VL* type work flow can be transformed into a *PL* one by transforming the activity cyclic loop into an activity chain. Figure 3.8 shows the conversion of the *VL* type work flow as shown in Figure 3.6 into a *PL* type work flow by adding a dumping activity to represent the actual transit activity from steel stockpiling area to the site entrance /exit. Such application is used for sharing of *MR* among multiple work flows.

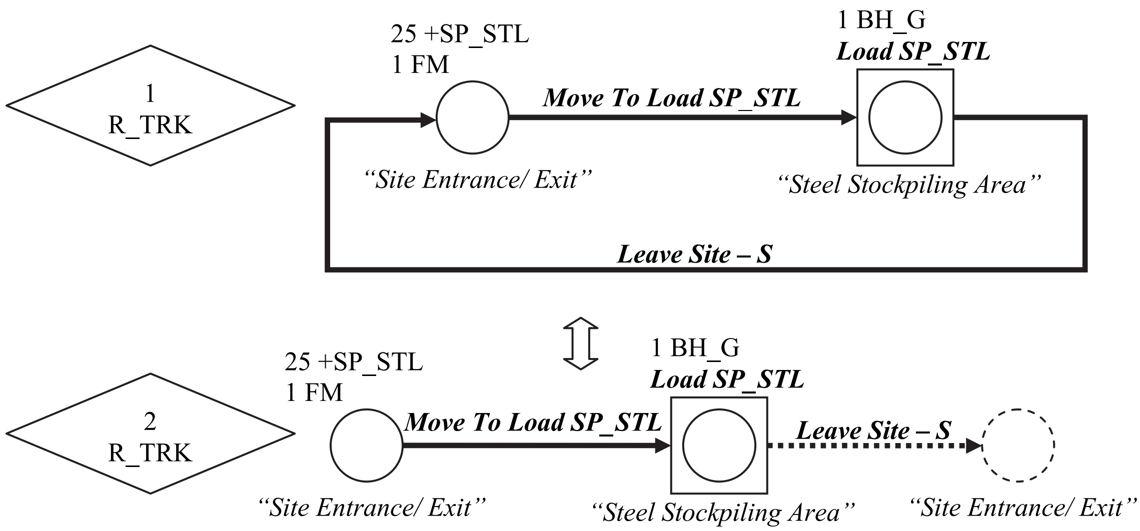


Figure 3.8. Conversion of a *VL* Type Work Flow into a *PL* Type Work Flow

As far as the *SDESA* simulation platform is concerned, the linkage between *work flows* is usually defined by logical sequences by means of specifying a disposable resource *(DR)* or imposing criteria on a control variable *(CV)*. In advanced settings, flow entities can also be generated by defining the flow entity arrival time and the time interval in different statistical distributions. Using the mining project in Indonesia as an example, the *Port trucks* are called once a week to deliver the settled iron ore stockpiled at site to the port. The flow entity can be defined by at every seventh day (7 Day x 8 working hours / Day x 60 minutes / hour = 3360 minutes). The arrival time of the *Call Port Truck* work flow is 3360 minutes (after the seventh day). Regular interval of every seven days after the first flow entity is defined by the setting of time interval as "Constant(3360)" minutes.

7. Determine the Activities in Work Flows

An activity can only be initiated when a Flow Entity flows into the activity. The activities in a work flow execute in turns subject to the readiness of required resources, including the disposable resource *(DR)* either in form of intermediate products or signals generated from previous work flows.

The activities in each work flow are either a production activity fixed at a specific location (similar to Activity-On-Node (AON) network diagramming technique for CPM) which was denoted by placing a square node around its corresponding *location circle* or a transit activity from one location to another (similar to Activity-On-Arrow (AOA) network diagramming technique for CPM).

Advanced settings in large civil engineering projects

Activity interruption is one of the important factors that can be included in the simulation models to reflect the uncertainties of the activities. Some activities are occasionally subject to interruptions that prolong the activity duration. In the Kai Tak Airport demolition project, the activities *Move To Landfill* and *Return To Site* were subjected to traffic jams, the interruption probability of 0.1 would be assumed with the interruption duration of uniform distribution between 10 minutes and 20 minutes for both activities.

8. Combine the Flow Entities with the Work Flows

After defining the work flows and their corresponding activities, the flow entities are combined with the activity chains using arrows to define the precedence relationship of the activities. Activities along the flow should be linked up by arrow and coherent with the logical sequences. It is necessary to make sure that the flow entity unit is consistent within every activity along the chain. For the production line type work flow, the total number of activities to be executed is the same as the number of flow entity assigned.

On the other hand, the activities in a vehicle loop type work flow will execute in turns continuously until either the disposable resources required to driven the activities have been consumed or the control variable's criteria for the execution of the activities are no longer met.

As shown in Figure 3.9, the general application procedures (Lu et al. 2007) are listed below:

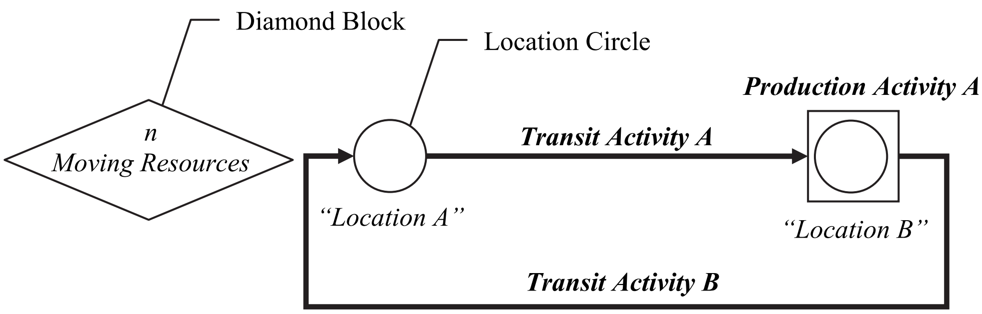


Figure 3.9. Definition of Process Mapping Model

1. Depict main work flows in the construction system by identifying the *Moving Resources (MR)* for each work flow, and circle key locations in the site space (location circles) by which *MR* pass and stop.

2. Within each work flow, identify all activities through which *MR* undergo, and then represent a *production activity* with a square node around its corresponding *location circle*; whereas a *transit activity* is denoted with an arrow linking its two *location circles* corresponding with its origin and destination locations.

3. Identify all the resources that need to be matched and used at each activity, including *Facilitating Resources (FR)* (manpower and machinery) and *Disposable Resources (DR)* (material or information units).
4. Enforce any additional precedence relationships between *production activities* defined at the same *location cycle*.
5. Specify activity durations as constants or distributions.
6. Specify additional transit times as required by *FR* in serving different activities at different locations in a datasheet format (i.e. what *FR* transits from which location to which location taking how long). Such information can later be kept in the *resource transit information system* (*RTIS*) of the simulation model as discussed in Procedure 9 below.
7. Initialize the quantity and the arrival times of *MR* available to each work flow in a *diamond block*, which is connected with a *location circle* where the *MR* resides at the start of operations. Also initialize the type and quantity of *FR* and *DR* available in a datasheet format, which is referred to as the *resource pool* of the simulation model.
8. Map *location circles* in each work flow onto their corresponding positions in a site layout model so as to complete the formulation of the simulation model in a site layout view. In general, a *production activity* is represented as a square block at a

location circle and a *transit activity* as a line section connecting two *location circles*.

9. Allocate Resources to Activities

The next step is to specify the resources required by and those released from activities according to the site operations. *Moving resources (MR)* and their quantities are defined in the work flows. *Facilitating resources (FR)* are stated in the initial resources. The initial amount of *disposable resources (DR)* is specified in the initial resources pool.

Advanced *SDESA* settings in large civil engineering projects

"Resource Transit Information System" *(RTIS)*:

RTIS is frequently adopted in the simulation models to model some resources that are shared among different work flows and activities. If a fixed routine cycle can be defined, the resources can be defined by fixed route and working schedule. Otherwise, the transit time for the resources among different locations can be defined in the *RTIS*.

In the Kai Tak Airport demolition project, the *Bulldozer* was shared between the activities *Grade Large Broken Concrete* and *Grade Small Broken Concrete*. The *Backhoe_General* was served for two activities – *Load Stockpiled Debris* and *Load Stockpiled Steel*. As shown in Table 3.2, *RTIS* states the transition duration for the resources moving between different locations.

Table 3.2. Resource Transit Information System

Resource	From	To	Transit Duration (min)
Bulldozer	KT-Small BC Stockpile	KT-Large BC Stockpile	0.5
Bulldozer	KT-Large BC Stockpile	KT-Small BC Stockpile	0.5
Backhoe	KT-Debris Stockpile	KT-Steel Stockpile	0.2
Backhoe	KT-Steel Stockpile	KT-Debris Stockpile	0.2

Substitute Resources:

Substitute resources are defined when two resources are applied in the project with one resource is preferred than the other one. Let a new compactor and an old compactor be the resource pair as an example. The old compactor is adopted as the substitute resource for the new compactor. The priority of usage of the older compactor is lower than that of the new compactor. When both the new and old compactors are available, the new compactor will be selected to carry out the road compaction activities. The older compactor would only be used when the new compactor is busy.

Resource Breakdown:

Resource breakdown is common in construction sites. No Probability of Breakdown (PBD) is required for those cases where there are standby resources ready on-site or the utilization rate of a particular resource type is low and with more than one resource available on-site. For new machinery, the chance of breakdown may be insignificant for a project with relatively short duration. On the other hand, the probability of breakdown for old machines is expected higher. The significance of resource breakdown depends on the significance to the overall production. Two components are concerned for the significance, namely the Probability of Breakdown (PBD) and the breakdown period.

10. Add Disposable Resource Entity

Disposable Resource Entity (DR) can be generated from activities and accumulated to initiate other activities. Generation of *DR* from activities is determined according to either the amount of intermediate materials or the number of signals for establishing the logical sequences among different *work flows*. This process defines the interdependent relationships among different *work flows* and activities.

An example is shown in Figure 3.10. The *Steel Stockpile* work flow comprises of four activities to load and transfer the steel to the stockpiling area for the collection of *Steel Recycling* work flow. Through quantity taking-off, for every 25 units of *Stockpiled Steel "25 SP_STL"* produced, the contractor will notice the steel recyclers to collect the *SP_STL*. The Recycler would then send a truck *"R_TRK"* to collect the *SP_STL*, a *flagman "1 FM"* would lead the truck to the *Steel Stockpiling Area* where the *SP_STL* was loaded by a backhoe *"1 BH_G"*. The truck would leave the site and await the signal for another cycle. The relationship between these two work flows was connected through the generation of one unit of *SP_STL Entity* at the end of *Unload to Steel Stockpile* activity. The *Steel Recycling* work flow will be activated when there are twenty-five *SP_STL* entities. This represents a ratio of 25 to 1, which is established for this work flow pair.

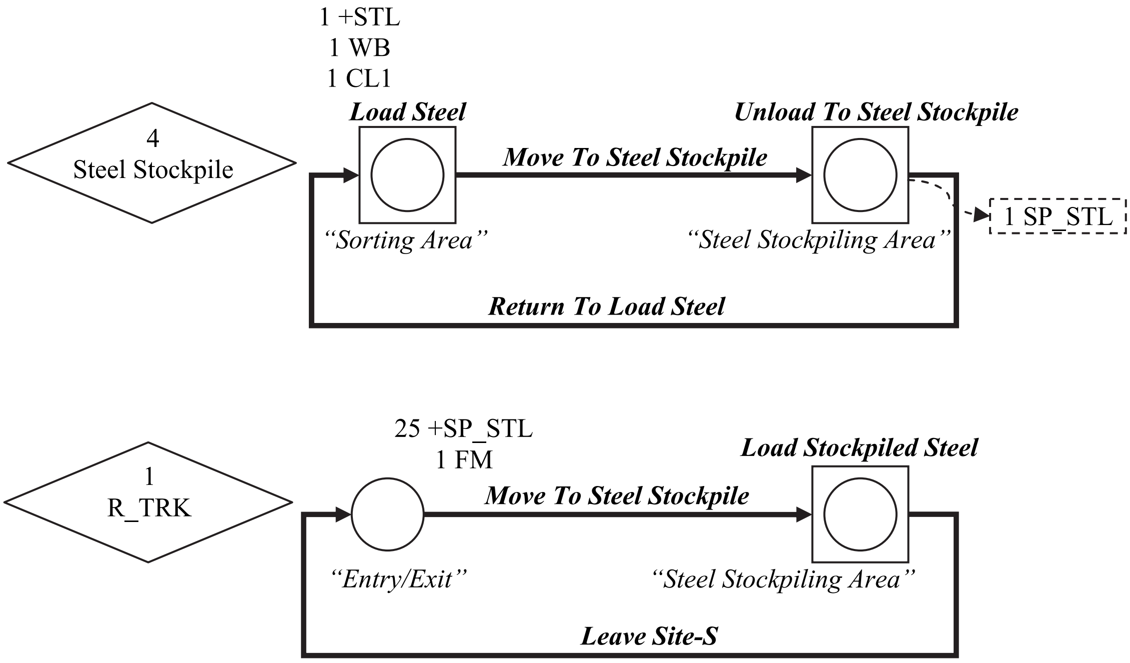


Figure 3.10. Process Mapping Model –Transportation of Steel and Steel Recycling Work Flow

11. Validate the Model

Similar to normal computer programming, model validation is an essential process in simulation modeling to debug the model by identifying any unexecuted work flows and unusual prolongation of activities. The initial model should be simplified as much as possible for model validation by exclusion of any advanced settings such as activity interruption, resources breakdown, and stochastic activity durations.

For simple simulation system, the model validation can be dry run through manual calculation for individual activities.

For large simulation system, it would be very difficult, if not possible, to carry out manual calculation. Instead, the model should be validated through contrast of overall production rate or cycle time against the estimated ones based on historical real projects or competent construction manager's review.

Advanced settings in large civil engineering projects

Alternatively, it is usually a good practice to subdivide the large simulation model into separate sub-models and validate them individually and integrate them together. For example, the mining project can be firstly divided into the iron ore processing plant and delivery activities from the ore-digging area and to the port, and then integrated with each other after model validation.

12. Refine the model

Control variables are often used in a simulation tool such as *SDESA* to enhance the flexibility of the simulation model. For a concreting example, the criteria for execution of an activity *transfer of concrete from the pump to the hopper* can be defined as when *hopper volume* is less than 0.2 cum and *pump volume* is greater than zero. After executing the activity, the modification would be the *hopper volume* increased by the *pump volume* and the *pump volume* becomes zero.

13. Review the model

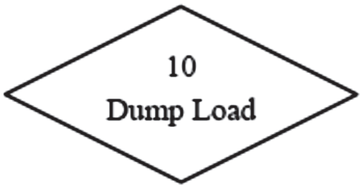
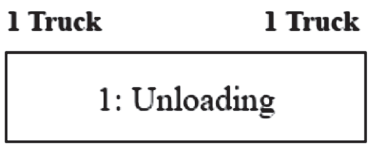
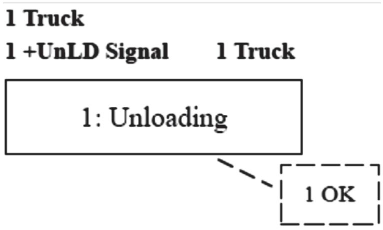
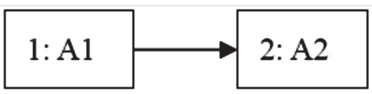
When the whole model is validated and refined, it should be reviewed to add advanced settings such as activity interruption, resources breakdown probability and duration, stochastic activity durations. It is also necessary to trim off any redundant elements to make the model concise before carrying out any system optimization and scenario analysis. The objective is to minimize the computing resources during detailed assessment without significant loss of accuracy on model interest. Procedures 1 to 13 should be checked carefully to make sure the model can accurately portray the real operation.

The model outputs on activity duration and resource utilization statistics are examined. Problems can be identified through prolonged waiting / idling of some of the resources, unusual utilization rates of the resources or bar chart output showing the activity sequences like the Gantt chart.

3.5 Terminology Definitions of *SDESA* Model

The *Simplified Discrete Event Simulation Approach (SDESA)* (Lu 2003) computer platform provides a convenient tool to showcase the application of the framework and prove the concept through case studies of an airport demolition project, a microtunneling project and a mining project. The basic model elements in *SDESA* are listed in Table 3.3. *SDESA* was developed through extracting the constructive features from the existing events/ activity-based simulation methods (Lu 2003).

Table 3.3. Model Elements of *SDESA* (Lu 2003)

Name	**Symbol**	**Description**
Flow Entity	 Diamond	**Flow Entity** is the head of a chain of activities (process), representing how many times the process is to be repeated, or the number of jobs to be handled. If the exact number of cycles or jobs are not know, a looping process is formed while the number of initial flow entities represents the number of jobs that are allowed to be handled concurrently. The looping will be terminated due to unavailability of resources, due to either total simulation time being over or no material/commands (disposable resource entities) being generated by another process.
Activity	 Rectangle	**Activity** is an operation or a task that consumes time and occupies resources, or either of them.
Resource Entity	 Resources Required: Top Left Corner Resources Released: Top Right Corner	Limited reusable **resources** including crew/equipment/tool/space; they can be shared by more than one activity or process.
Disposable Resource Entity	 Entities Required: Top Left Corner Entities Generated: In Dashed Box	**Disposable Resource Entities** are either intermediate products (materials) or command units (signals) that are generated by one activity and required by another; they can be utilized for once only. They play the key role to setup the interdependent relationships between various activities/processes.
Arrow	 Arrow: From Precedence to Successor	Analogous to CPM, **arrows** link up activities to denote the logic/technological precedence relationships.

3.6 An Illustration Example: Road Base Construction

A road granular base course construction example as shown in Figure 3.11 is used to illustrate how to adopt the framework to establish a process mapping model. A heavy construction contractor would decide how many dump trucks he should rent to match up with his two loaders in building the 1.2 km long road work. To facilitate the planning and control, the contractor divided the road work evenly into 25 sections, each being 40 m long and requiring 120 cum granular aggregates. The original travel distance between the quarry and the construction site was 5 km, which was extended by 0.1 km with every 250 cum of aggregates delivered to the site. The contractor was to rent a total of 6 dump trucks and hire one employee who directed the trucks to unload the aggregates to the road sections and to operate the water truck to moisten a graded section before compacting it. The procedures to establish the process mapping model are defined as follow.

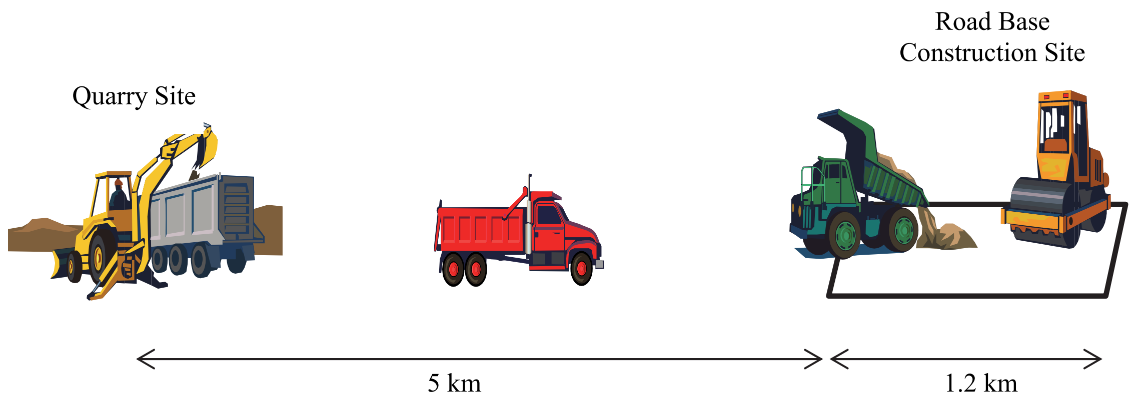


Figure 3.11. Road Granular Base Course Construction Example

1. Define Simulation Objectives

The simulation objective was to assist the decision making for the best combination of big and small dump trucks to rent to match up with his two loaders in building the 1.2 km long road work. The best option to be obtained would be the one with the least total rental cost, calculated by the product of unit rental cost of trucks in dollars per hour and average project duration.

2. Define the Scope of Process Mapping Model

The location boundary includes a road base construction site of 1.2 km in length and a quarry site located 5 km away from it.

3. Collect Project Data

Operational details of big and small dump trucks are estimated from literatures or text books, whereas the rental cost of the dump trucks can be sourced from leasing companies or competent construction managers. The key information is summarised in Table 3.4.

Table 3.4. Information of Road Granular Base Course Construction Example

	Big dump truck	Small dump truck
Actual quantity per truck	12 cum	8 cum
Travel speed (fully loaded)	Tri (50, 55, 65) km/h	Tri (45, 50, 60) km/h
Travel speed (empty)	Unif (55, 65) km/h	Unif (50, 60) km/h
Unloading time	Unif (3,6) min	Unif (2,4) min
Rental cost	$100/hr	$90/hr

4. Outline Site Layout and Key Locations

The site layout can be outlined as the rural quarry site and the road base construction site with adjustable working zone throughout the construction process.

5. Specify Model Assumptions

Assumptions on the status of working conditions: the quality of work and the safety management should reach such satisfactory standards that the site management process would not be interrupted; and weather and temperature were consistently fine and suitable for work.

Assumption on time: the simulation of the process was assumed to be continuous work flow.

Assumptions on space: the truck delivery capacities of large and small trucks were assumed to be 12 cum and 8 cum respectively.

Assumptions on resources: the normal production rate for each loader was 2 cum per minute. One grader, one water truck, and one roller were employed in the site and the mean duration to grade, moisten, and compact each road section were 10 min, 5 min and 18 min respectively.

<u>6. Determine Flow Entities</u>

As shown in Table 3.5, the flow entities in this model include two vehicle loop flow entities, namely *small dump trucks* and *big dump trucks*, for the delivery cycles and one production line work flow of *road section construction*. As a total of six trucks would be rented, let x and $6\text{-}x$ be the numbers of small and big dump trucks rented respectively for scenario analysis.

Table 3.5. Work Flows and Their Corresponding Work Units for Road Base Construction

Work Flow	**Basic Model Structure (Vehicle Loop (V) / Production Line (P))**	**No. of Work Units**	**Disposal Resources Required**	**Disposal Resources Generated**
Small Dump Truck	V	x	8 *Dump Load*	8 *granules on-site*
Big Dump Truck	V	$6\text{-}x$	12 *Dump Load*	12 *granules on-site*
Road Section Construction	P	25	120 *granules on-site*	-

<u>7. Determine the Activities in Work Flows</u>

The activities in the *Small Dump Truck* and *Big Dump Truck* flow entities include

Loading of Aggregates to the Truck, *Delivery to Site*, *Unload Aggregates at the Road Base Construction Site* and *Return to Quarry Site*. The activities in the *Road Section Construction* work flow include *Grading of the Aggregates, Moistening and Road Compaction*.

8. Combine the Flow Entities with the Work Flows (Activity Chains)

The *Small Dump Truck* and *Big Dump Truck* flow entities are combined with activities *Loading of Aggregates to the Truck*, *Delivery to Site*, *Unload Aggregates at the Road Base Construction Site* and *Return to Quarry Site*. The *Road Section Construction* work flow is combined with activities *Grading of the Aggregates, Moistening* and *Road Compaction*.

9. Allocate Resources on Activities

A new loader *(NLD)* and an old loader *(OLD)* were applied to load the crushed rocks to the trucks. The old loader was adopted as a substitution resource for the new loader. The priority of usage of older loader is lower than the new loader. When both the new and old loaders were available, the new loader would be selected to carry out the loading activities. The older loader would only be used when the new loader was busy. The resources are defined in Table 3.6.

Table 3.6. Resource Pool for Road Base Construction Example

Resource Class	Resource Type	Code	Amount
Moving Resource (MR)	Small Dump Truck	Small D-Trk	x
	Big Dump Truck	Big D-Trk	6-x
Facilitating Resource (FR)	New Loader	NLD	1
	Old Loader	OLD	1
	Flagman	FLM	1
	Grader	GRD	1
	Water	WTR	1
	Roller	ROL	1
Disposable Resource (DR)	Dump Load	Dp_Ld	0
	Granule on-site	Grn_On_Site	0

<u>10. Add Disposable Resource Entities</u>

Disposable resources are defined to control the quantity of work to be carried out. The loading activities load the aggregates to the dump trucks until the construction work of 1.2 km completed. Eight and twelve *granular units* are taken up by the small and big dump trucks respectively. Those granules would be unloaded on-site as eight and twelve *granules on-site*. The grader would grade the road section for every 120 *granular units dumped on-site*. The construction work completes when 25 sections of road construction are carried out. The disposable resource entities for road base construction are listed in Table 3.7.

Table 3.7. Disposable Resource Entities for Road Base Construction

Activity	Disposal Resources Required	Disposal Resources Generated
Load to Small Dump Truck	8 *granules*	-
Load to Big Dump Truck	12 *granules*	-
Unloading by Small Dump Truck	-	8 *granular units on-site*
Unloading by Big Dump Truck	-	12 *granular units on-site*
Road Section Construction	120 *granular units on-site*	-

Based on the above setting, the process mapping model of a road base construction is shown in Figure 3.12.

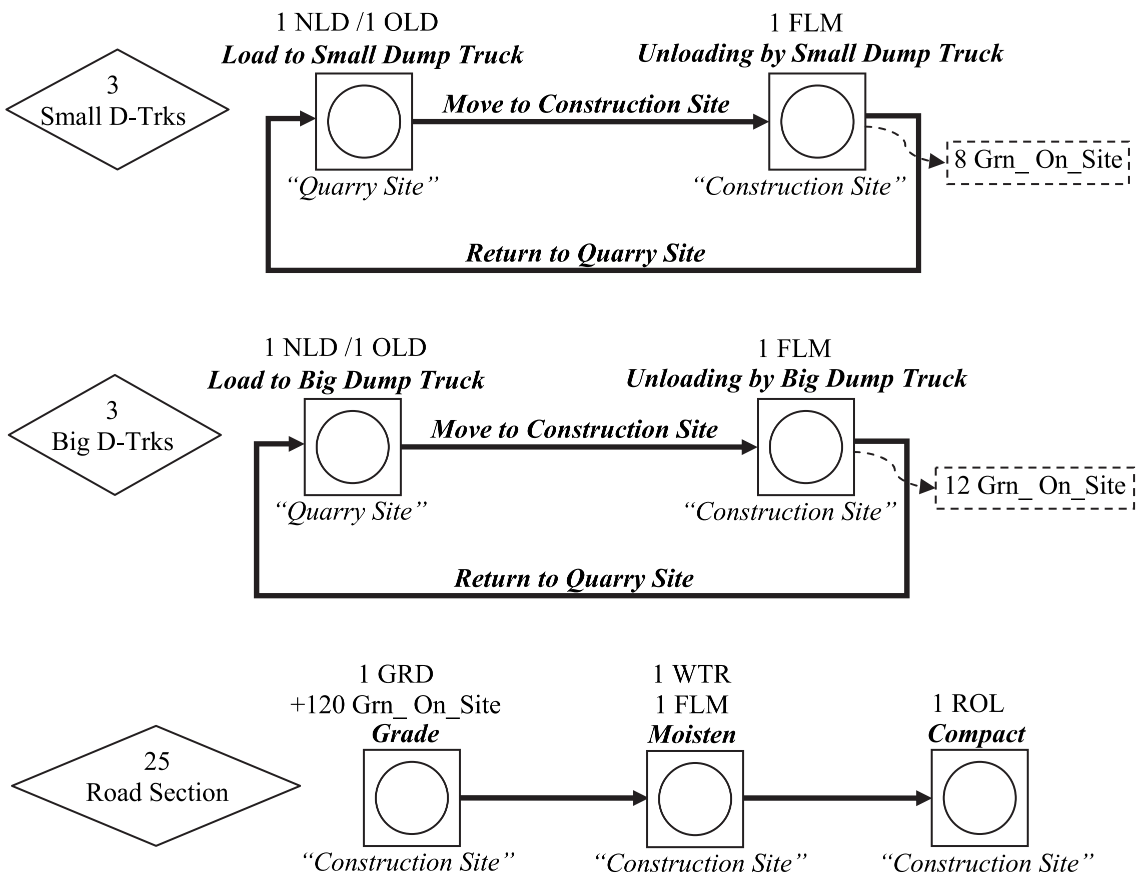


Figure 3.12. Process Mapping Model of a Road Base Construction Site

11. Validate the Model

The event against the simulation time output is examined to check if there is any unusual activity delay or resource idling arising from incorrect model settings. The animation of simulation output is observed to validate the logical sequences of the work flows and activities.

12. Refine the Model

In order to accurately take into account the changing travel distance and the corresponding traveling time between the quarry site and the road base construction section, a *CV "Travel_Dist"* is used to define the changing travel distance and the corresponding travel time is defined as "*Travel_Dist* / Tri(45,60,50) *60" (Distance divided by time in minutes).

A *CV "Quantity-Counter"* is introduced to counting the quantity of granules arrived on-site. For every *Dump* activity by the small trucks, *Quantity-Counter* increases by 8 cum. Similarly, *Quantity-Counter* increases by 12 cum for every *Dump* activity by the big trucks. When *Quantity-Counter* accumulates greater than or equal to 250 cum, it will trigger a dummy *Distance Adjustment* work flow to adjust the distance. The modifications of the control variable would be: 1) *Travel_Dist* increased by 0.1 km and 2) *Quantity-Counter* decreased by 250 cum after the adjustment of *Travel_Dist* for resetting the counter.

13. Review the Model

Once the model is refined, the details of old loader can be included. The probability of breakdown (PBD) is defined as 0.1 (10 percent) with a duration of "Beta 4 points (minimum = 10, maximum = 30, Q_l = 15, Q_u = 20)" in minutes. The new loader is in good running conditions and no breakdown is anticipated. Stochastic distribution of activity durations is assigned to the model.

14. Convert the Process Mapping Model to a Simulation Model

The process mapping model of the road base construction project as shown in Figure 3.12 is converted into a *SDESA* model as shown in Figure 3.13. Not much modification was included except the dummy *Distance Adjustment* work flow adopted for adjustment of travel distance and time between the quarry site and road base construction site.

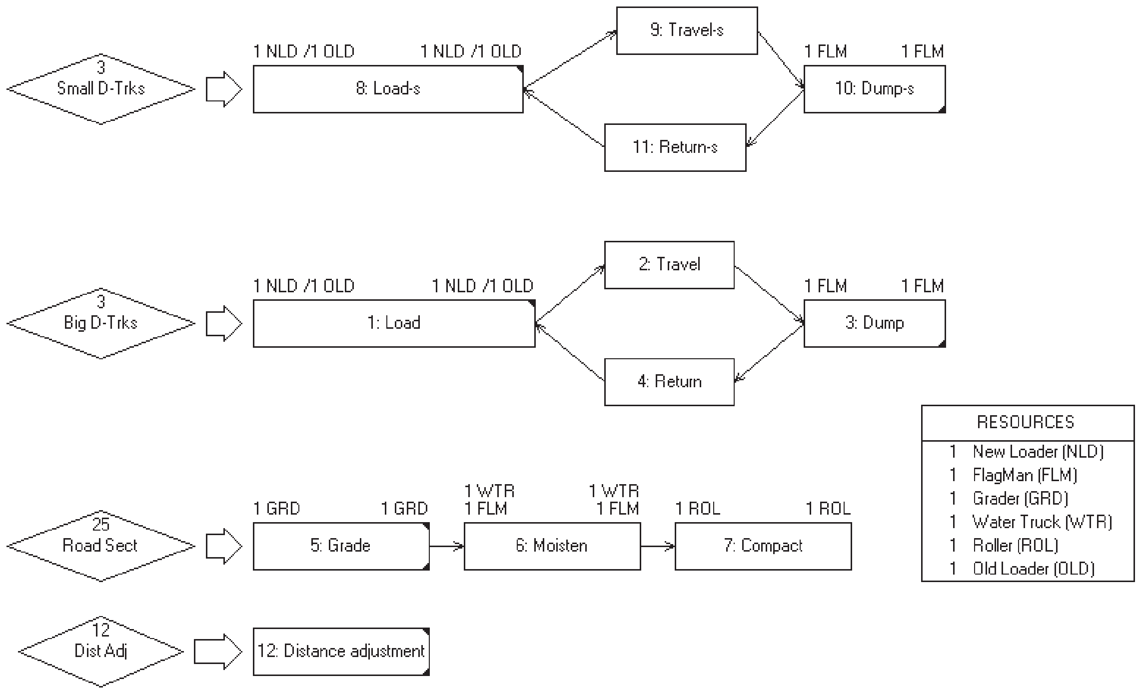


Figure 3.13. Refined Model of a Road Base Construction Site

The activity property of *Dump by Small Truck* Activity is shown in Figure 3.14. The control variable modifications are listed in the property box.

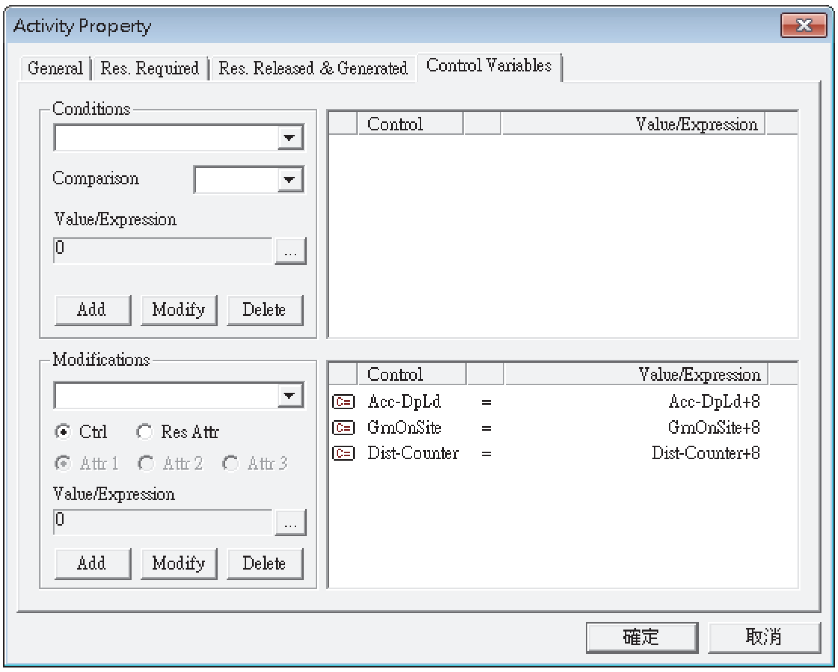


Figure 3.14. Property of *Dump by Small Truck* Activity

The resource type settings in *SDESA* model is shown in Figure 3.15. The resource breakdown for the *Old Loader (OLD)* is included in the settings.

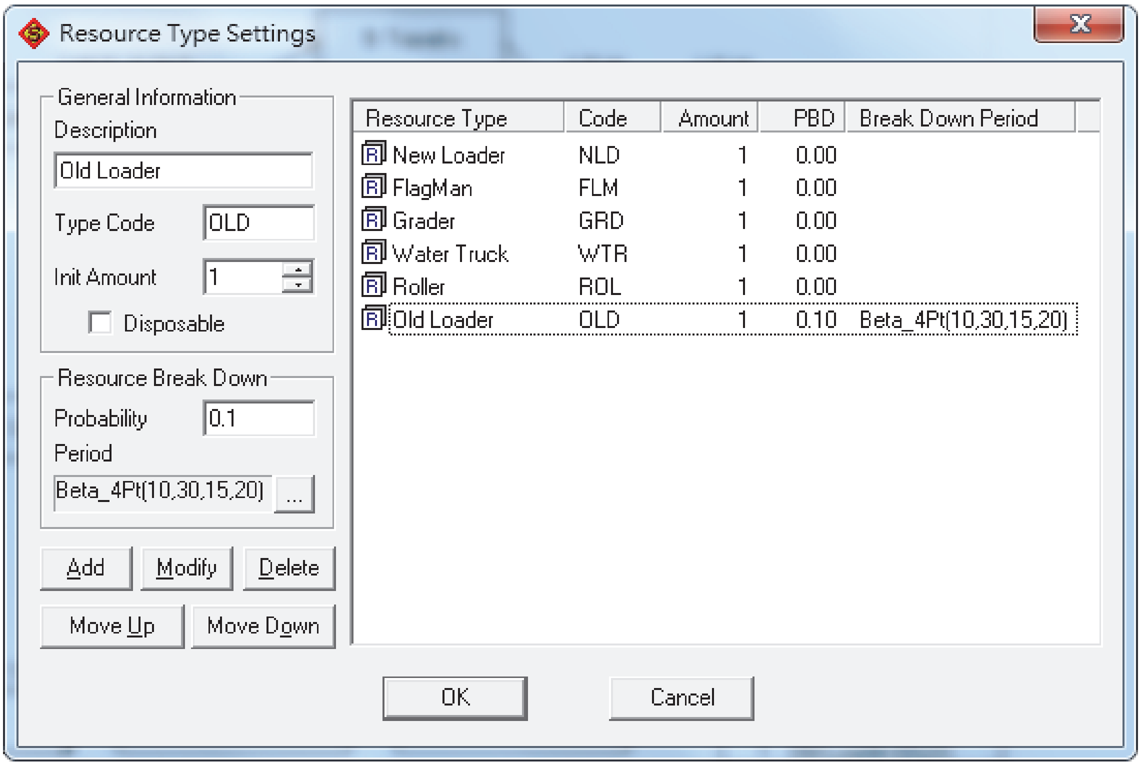


Figure 3.15. Resource Type Setting for "Old Loader" in a Road Base Construction Site

As shown in Figure 3.16, the simulation visual output is carried out for the single run case for model validation through visual examination of the processes. After model validation, multiple runs were carried out for scenario analysis using Monte Carlo simulation.

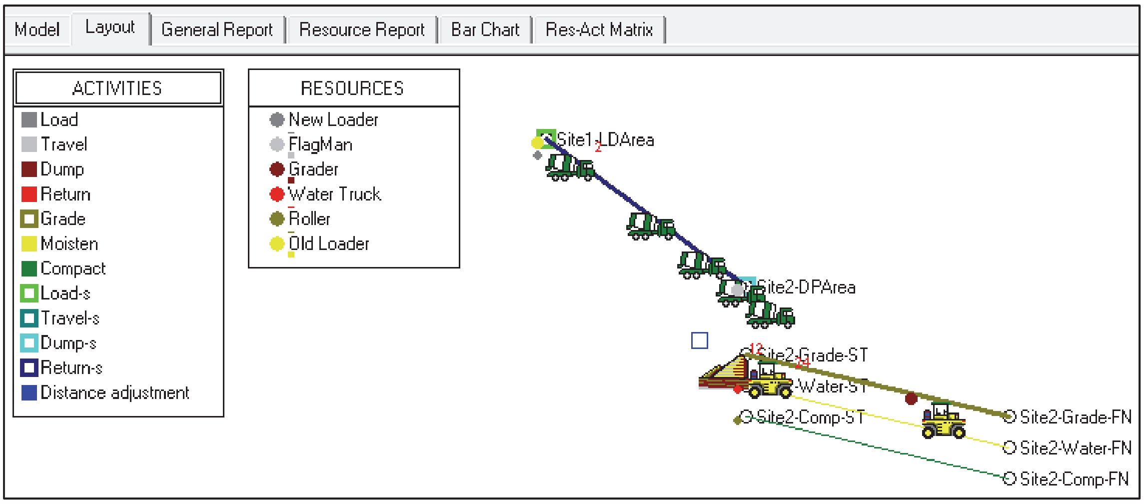


Figure 3.16. Animation of a Road Base Construction Site

3.7 Process Mapping Model: Case of Kai Tak Airport Demolition Project in Hong Kong

The formal framework for simulation approach and process mapping model is applied to a case study of Kai Tak Airport demolition project in Hong Kong. The *SDESA*-based computer application of the framework will be discussed in Chapter 4.

In the airport demolition project, selective demolition was adopted for the sorting of construction waste to maximize the recycle rate, the scope of construction process in the simulation was firstly defined as from the time when the structures and buildings were demolished to the time when materials were temporarily stockpiled onsite or collected to designated locations off site. The site layout was then defined based on site map which was normally available during the design stage. The site layout design would be carried out based on simulation results to effectively allocate the material stockpiling areas.

1. Define Simulation Objectives

The simulation objective is to evaluate the cost efficiency of waste handling practice on the Kai Tak Airport demolition project in Hong Kong and postulate alternative resource provision scenarios to assist site management and decision making.

2. Define the Scope of Process Mapping Model

Geographical boundary of the model was defined as the site boundary of the airport demolition site, with the supplementary waste collection route to the public landfill site. The process mapping model includes 1) raw demolition waste collecting and sorting; 2) broken concrete sieving and stockpiling; 3) steel bar recycling and 4) debris disposal at landfill.

On the other hand, the trucks for steel recycling collection were not operated under the Contractor. Only scheduling of steel collection was concerned about, whereas the subsequent steel delivery and recycling activities were out of scope of the site management system and could be ignored in site layout planning and process mapping model. The steel collection activities were condensed to a single activity in the process mapping model.

The project lasted for years with similar select demolition procedures carried out from a building to all the others. It is not practicable to run a full model due to limited computer power. Section 4.2.2 demonstrates the preliminary tests carried out to decide optimum simulation model size. The tests with different scales from $\frac{1}{1440}$x to $\frac{1}{10}$x of the actual total quantity of broken concrete production to the actual system were compared. Table 3.8 summarizes the total duration, nominal production rate and process time of model of different scales from $\frac{1}{1440}$x to $\frac{1}{10}$x. The production rate is plotted against the simulation time as shown in Figure 3.17. The larger is the simulation size, not only the higher is the model accuracy, but also the longer is the computing time. The selection of model scale should compromise the simulation time and modeling accuracy. The $\frac{1}{40}$x of actual total quantity of broken concrete production to the actual system was finally adopted. Further system optimization and scenario analysis were carried out based on the scaled model.

Table 3.8. Simulated Production Rate and Process Time of Model of Different Scales

	Ratio of Model Scale to Actual Work	**Broken Concrete Produced (unit)**	**Total Duration (min)**	**Process Time (h:m:s)**	**Entity Processed**	**Simulated Production Rate (unit/min)**
Actual	1:1	1154000	162240	-	-	7.11
Simulation	$\frac{1}{10}$x	115200	11704	1:18:53	36000	9.73
Simulation	$\frac{1}{40}$**x**	**28800**	**3017**	**0:04:59**	**9000**	**9.55**
Simulation	$\frac{1}{160}$x	7200	821	0:00:20	2250	8.77
Simulation	$\frac{1}{1440}$x	800	168	0:00:01	250	4.76

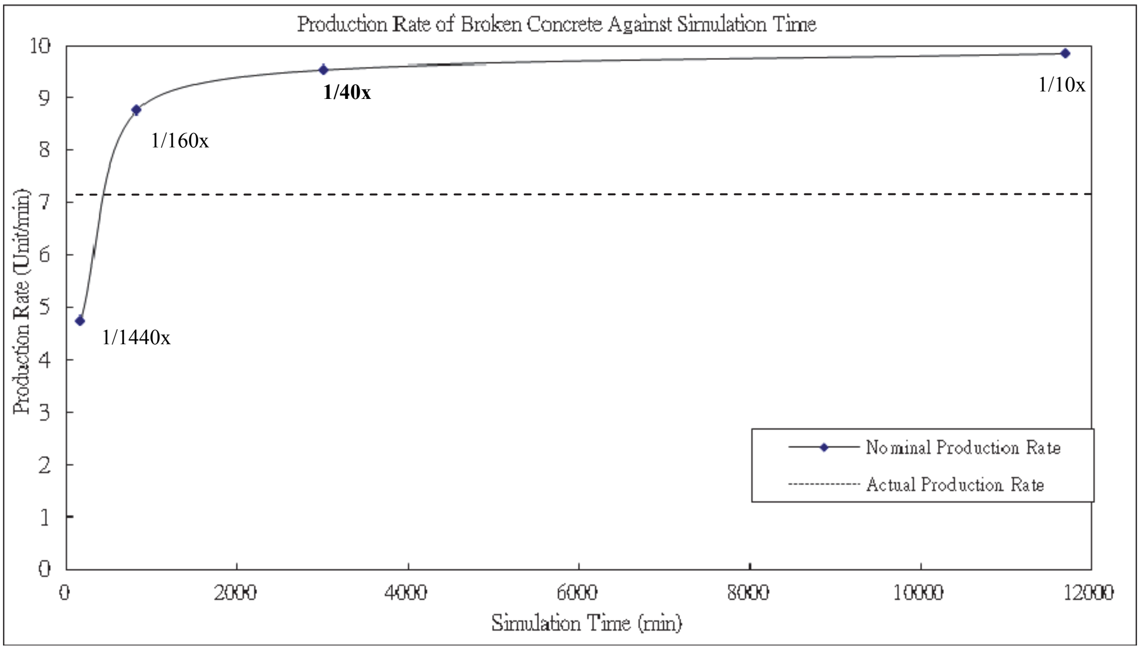


Figure 3.17. Production Rate against the Simulation Time

3. Collect Project Data

Project information was collected through interviewing engineers of Civil Engineering and Development Department (the Client), site visits, interviews and eliciting relevant project information of resident site staff including engineers and inspectors of the Consultant and site engineers and foremen of the Contractor.

4. Outline Site Layout and Key Locations

Site layout plan of the project is shown in Figure 3.18. Site locations of different activities were overlaid to the site layout plan to valid the site operations. Key locations in the site space are circled as location circles in the mapping process and listed in Table 3.9.

Table 3.9. Key Locations of Kai Tak Airport Demolition Project

Location	**X**	**Y**
Demolition	165	335
Sorting	225	315
Sieving	225	270
Steel Stockpile	275	295
Debris Stockpile	320	315
Small BC Stockpile	340	95
Large BC Stockpile	320	55
Site Entrance / Exit	555	350

Note: XY relative coordinates taken from site layout plan

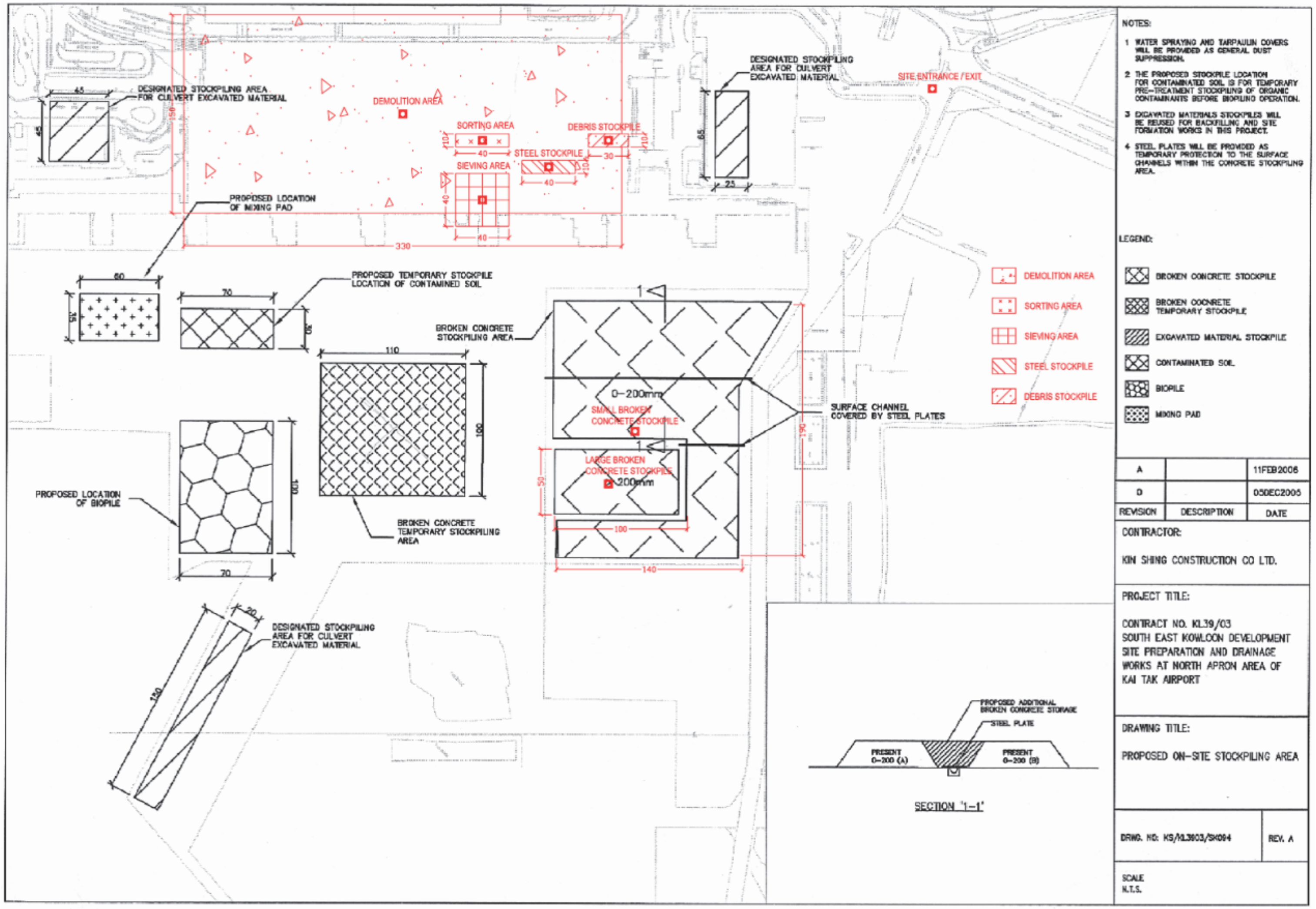


Figure 3.18. Site Layout of the Kai Tak Airport Demolition Project

5. Specify Model Assumptions

According to the first-hand information obtained from the site, the following assumptions were made in establishing the simulation model:

1. Weather and temperature were consistently fine and suitable for work.
2. The number of working hours per day was eight, plus a one-hour lunch break (12:00-13:00.)
3. The constituents of the waste material could be segregated by waste sorting and handling mechanisms being applied. For instance, the extraction of *Steel (STL)*, *Broken Concrete (BC)* and non-usable *Debris (DB)* from *Raw Demolition Units (RDU)* by sorting; the segregation of *Broken Concrete (BC)* into *Large Broken Concrete (LBC) and Small Broken Concrete (SBC)* by sieving.
4. The volume of the waste material reduced after compaction. For example, after each truck load ($4.5m^3$) of the *Stockpiled Small Broken Concrete* or the *Stockpiled Large Broken Concrete* compacted by the bulldozer, $4.0m^3$ (instead of $4.5m^3$) of *Graded Small Broken Concrete* or *Graded Large Broken Concrete* would be produced.

6. Determine Flow Entities

Major work flows are identified and their corresponding work units are listed in Table 3.10.

Table 3.10. Work Flows and their Corresponding Work Units in Kai Tak Airport Demolition Project

Work Flow	**Basic Model Structure (Vehicle Loop (V) / Production Line (P)**	**No. of Work Units (1000 RDU)**	**Disposal Resources Required**	**Disposal Resources Generated**
Transport RDU to Sorting Area	V	3	1000 *R_DU*	40 *RDU*
Sort DU into BC, STL and DB	P	50	20 *DU*	1 *STL,* 1 *DB,* 18 *BC*
Steel Stockpile	P	50	1 *STL*	1 *SP_STL*
Debris Stockpile	P	50	1 *DB*	1 *SP_DB*
Transfer BC to Sieving Area	V	1	5 *BC*	5 *S_BC*
Sieve BC into SBC/ LBC	P	180	5 *S_BC*	4 *SBC,* 1 *LBC*
Small BC Stockpile	V	2	45 *SBC*	45 SP*_SBC*
Large BC Stockpile	V	2	45 *LBC*	45 *SP_LBC*
Grade Small BC	P	16	45 *SP_SBC*	40 *G_SBC*
Grade Large BC	P	4	45 *SP_LBC*	40 *G_LBC*
Steel Recycling	V	1	25 *SP_STL*	-
Debris Disposal	V	1	50 *SP_DB*	50 *D_DB*

One production line type *Sieving* work flow is shown in Figure 3.19. One vehicle loop type *Steel Recycling* work flow is shown in Figure 3.20.

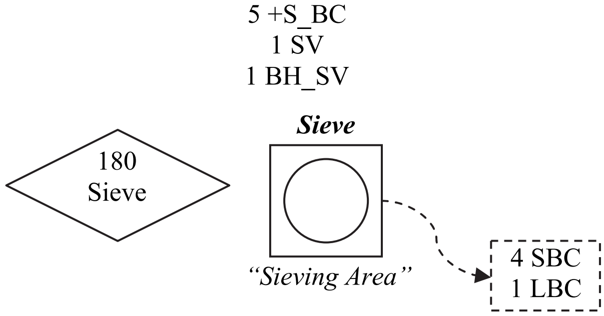


Figure 3.19. Process Mapping Model – Sieving Work Flow

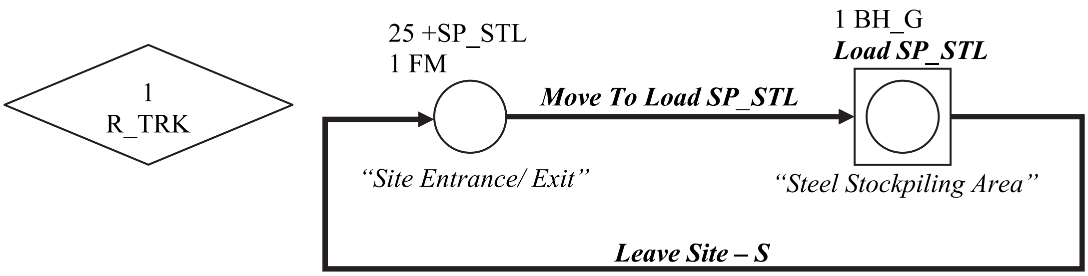


Figure 3.20. Process Mapping Model – Steel Recycling Work Flow

<u>Conversion of *VL* Type Work Flows into *PL* Type Work Flows</u>

After sorting the *Demolition Units*, the *Steel "STL"* and the *Debris "DB"* would be transported and stockpiled from *Sorting Area* to the *Steel Stockpiling Area* and the *Debris Stockpiling Area* respectively. The two material handling processes required the same resources, a *Wheelbarrow "WB"* as the *moving resource (MR)* and a *Cleaning Labour "CL"* as the *facilitating resource (FR)*.

Note that the traditional use of two individual *VL* type work flows by assigning two *WB's* to each work flow cannot mirror the flexibility of resource sharing in practical situations (four *WB's* were shared between the deliveries of *STL* and *DB*). Instead, two *PL* type work flows are adopted to achieve such purpose. *Steel Stockpile* requires the availability of the combination of one *WB* (*MR*) with one *Steel "1 STL" (DR),* whereas *Debris Stockpile* requires the availability of the combination of *"1 WB" (MR)* with one *Debris "1 DB" (DR)*. The number of *MR* are defined the resource pool for the work flows representing the maximum number of concurrent work tasks.

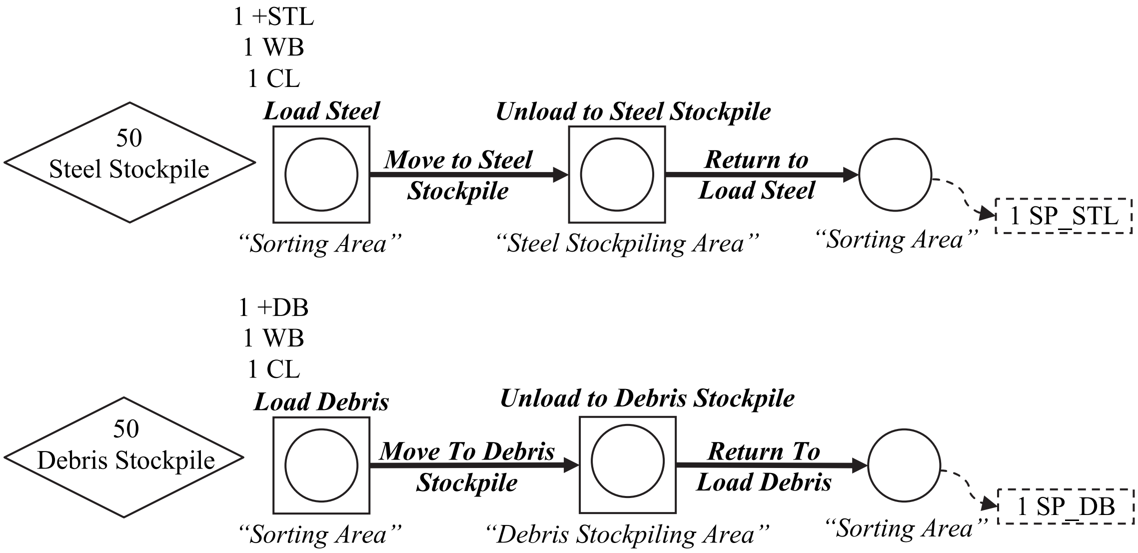


Figure 3.21. Process Mapping Model – Transportation of Steel and Debris Work Flow

As shown in Figure 3.21, by using two *PL* type work flows: *"Steel Stockpile"* and *"Debris Stockpile"*, the four *WB's* can now be shared between the delivery cycles by combining with respective *DR's*. As there are four *WB's* available, the numbers of resources are equal to the maximum number of concurrent work tasks which is four. The work flows will be executed once there is any free *WB* and its driver *CL*, together with the presence of *STL* or *DB* units; upon delivery the materials to their corresponding destinations, one unit of *Stockpiled Steel "1 SP_STL"* or one unit of *Stockpiled Debris "1 SP_DB"* will be produced for *Steel Recycling* and *Debris Disposal* work flows respectively. Table 3.11 shows the location boundaries of work flows.

Table 3.11. Location Boundaries of Work Flows in Kai Tak Airport Demolition Project

Work Flow	**Location Boundaries**	
	Location 1	**Location 2**
Transport *RDU* to Sorting Area	Demolition	Sorting
Sort *DU* into *BC*, *STL* and *DB*	Sorting	-
Steel Stockpile	Sorting	Steel Stockpile
Steel Recycling	Site Entrance/ Exit	Steel Stockpile
Debris Stockpile	Sorting	Debris Stockpile
Debris Disposal	Debris Stockpile	Landfill
Transfer *BC* to Sieving Area	Sorting	Sieving
Sieve *BC* into *SBC*/ *LBC*	Sieving	-
Small *BC* Stockpile	Sieving	Small BC Stockpile
Large *BC* Stockpile	Sieving	Large BC Stockpile
Grade Small *BC*	Small BC Stockpile	-
Grade Large *BC*	Large BC Stockpile	-

<u>7. Determine the Activities in Work Flows</u>

Activities comprising each work flow along with activity times in the form of uniform distributions or constants are summarized in Table 3.12.

Table 3.12. Activity Definitions of the Kai Tak Airport Demolition Project

Work Flows	Activities	Duration Input Model (min)		
		Type	L	U
Trucking Raw Waste	Load Demolition Unit	Uniform	7	9
	Move To Sort	Uniform	0.4	1
	Unload to Sort	Uniform	0.4	0.7
	Return to Demolition	Uniform	0.3	0.7
Sorting Raw Waste	Sort Raw Waste	Uniform	3	3.5
Stockpiling Steel	Load Steel	Uniform	0.8	1.2
	Move To Steel Stockpile	Uniform	0.5	0.8
	Unload To Steel Stockpile	Uniform	0.3	0.5
	Return to Load Steel	Uniform	0.3	0.6
Stockpiling Debris	Load Debris	Uniform	0.8	1.2
	Move To Debris Stockpile	Uniform	0.6	1
	Unload To Debris Stockpile	Uniform	0.3	0.5
	Return to Load Debris	Uniform	0.4	0.7
Trucking BC To Sieve	Load Broken Concrete	Uniform	0.2	0.25
	Move To Sieve	Constant	0.08	
	Unload To Sieve	Constant	0.1	
	Return to Load Broken Concrete	Constant	0.05	
Sieving BC	Sieve BC	Uniform	0.3	0.5
Stockpiling Small BC	Load Small BC	Uniform	4	5.5
	Move To Small BC Stockpile	Uniform	0.5	0.7
	Unload To Small BC Stockpile	Uniform	0.3	0.5
	Return to Load Small BC	Uniform	0.3	0.5
Stockpiling Large BC	Load Large BC	Uniform	4	6
	Move To Large BC Stockpile	Uniform	0.4	0.6
	Unload To Large BC Stockpile	Uniform	0.3	0.5
	Return to Load Small BC	Uniform	0.2	0.3
Grading Small BC	Compact Small BC	Uniform	3	4.5
Grading Large BC	Compact Large BC	Uniform	4	5
Disposing Debris	Load Stockpiled Debris	Uniform	5	8
	Leave Site - D	Uniform	2	3
	Move To Landfill	Uniform	25	30
	Unload to Landfill	Uniform	5	15
	Return To Site	Uniform	20	25
	Return to Load Debris	Uniform	1	2
Recycling Steel	Move To Load Stockpiled Steel	Uniform	1.5	3
	Load Stockpiled Steel	Uniform	5	10
	Leave Site - S	Uniform	2	4

Note: L = lower limit; U = upper limit.

As detailed site operations data were not kept by the contractor or the consultant, simulation input models (uniform distributions for activity times) were based on limited information available (observations by research personnel and estimates by site personnel.) The stochastic activity durations for site operations were input into the model for statistical analysis of overall production.

8. Combine the Flow Entities with the Work Flows (Activity Chains)

The *Collection of Raw Demolition Unit* work flow is used to demonstrate the combination of flow entities with the work flows (activity chains).

Figure 3.22. Demolition Work at Demolition Area

At the beginning of the whole process, the *Raw Demolition Unit (R_DU)* was stockpiled (Figure 3.23) at the location where the structural elements were originally demolished from top to bottom as shown in Figure 3.22. The *R_DU* was then collected by three specific backhoes *(BH_RDU)* to three specific trucks *(TRK_RDU)* assigned for transporting *RDU* to the sorting area.

(a)

(b)

Figure 3.23. *Raw Demolition Unit (R_DU)* Stockpiles at Demolition Area

At the beginning of the whole process (at time=0), the control variable *Raw Demolition Unit (R_DU)* was defined to control the total amount of *R_DU* to be handled. *R_DU*s were loaded by three specific backhoes *(BH_RDU)* to three specific trucks *(TRK_RDU)* whose volume capacity were 40 units each and transported to the sorting area.

As shown in Figure 3.24, two location circles, *Demolition Area* and *Sorting Area*, were defined in the *Truck for Raw Demolition Unit* (*TRK_RDU*) work flow, with two production activities (i.e. *Load Demolition Unit* and *Unload To Sort*) and two transit activities (i.e. *Move To Sort* and *Return To Demolition*). In the *Collection of Raw Demolition Unit* work flow, the activity *Load Demolition Unit* was initiated by the available *Raw Demolition Unit "R_DU"*, i.e. *"R_DU >0"* (When there existed "*R_DU"* on-site). Once the *Load Demolition Unit* activity is completed (i.e. forty units of *R_DU,* "*40 R_DU",* was loaded to truck), a modification of this control variable is given as *"R_DU = R_DU - 40"* (i.e. the total amount of *R_DU* was deducted by 40 units). The activity will stop only when all the pre-defined number of "*R_DU"* have been processed. For each cycle, 40 units of *Demolition Units (40 DU)* were generated at the end of the *Unload To Sort* activity as an intermediate material unit to the sorting process.

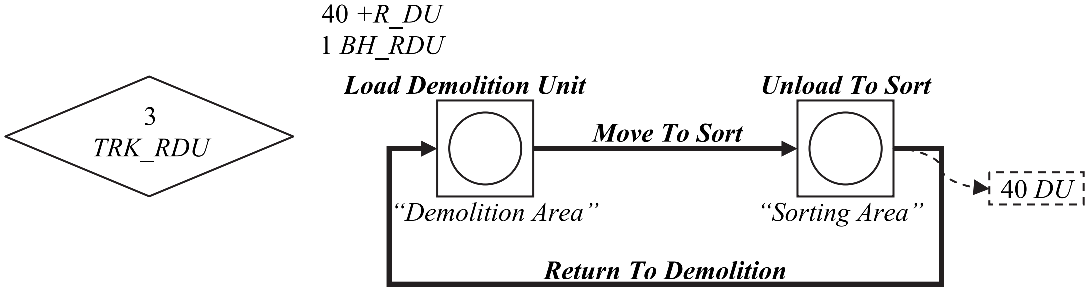


Figure 3.24. Mapping Model of Collection of Raw Demolition Unit Work Flow

9. Allocate Resources on Activities

Different types of resources were defined in Table 3.13.

Table 3.13. Resource Pool for Kai Tak Airport Demolition Project

Resource Class	Resource Type	Code	Amount
Moving Resources (MR)	Backhoe_Transfer to Sieve	BH_TTS	1
	Recycler's Truck	R_TRK	1
	Truck_Debris	TRK_DB	1
	Truck_Raw Demolition Unit	TRK_RDU	3
	Truck_Stockpilng	TRK_SP	2
	Wheelbarrow	WB	4
Facilitating Resources (FR)	Bulldozer	BDZ	1
	Backhoe_General	BH_G	1
	Backhoe_Raw Demolition Unit	BH_RDU	1
	Backhoe_Stockpiling	BH_SP	1
	Backhoe_Sorting	BH_ST	2
	Backhoe_Sieving	BH_SV	1
	Breaker	BRK	2
	Cleaning Labour	CL	4
	Flagman	FM	1
Disposable Resources (DR)	Demolition Unit	DU	0
	Steel	STL	0
	Stockpiled Steel	SP_STL	0
	Debris	DB	0
	Stockpiled Debris	SP_DB	0
	Disposed Debris	D_DB	0
	Broken Concrete	BC	0
	Sorted Broken Concrete	S_BC	0
	Small Broken Concrete	SBC	0
	Large Broken Concrete	LBC	0
	Stockpiled Small Broken Concrete	SP_SBC	0
	Stockpiled Large Broken Concrete	SP_LBC	0
	Graded Small Broken Concrete	G_SBC	0
	Graded Large Broken Concrete	G_LBC	0

The Steel Recycling work flow is shown in Figure 3.25, upon the Stockpiled Steel (*SP_STL*) accumulated reaching 25 units, the contractor would notice the steel recyclers to collect the *SP_STL*. The Recycler would then send a truck (*R_TRK*) to collect the *SP_STL*, a flagman (1 *FM*) would lead the truck to the "Steel Stockpiling Area" where the *SP_STL* was loaded by a backhoe (1 *BH_G*). The truck would leave the site and await the signal for another cycle.

Moving Resource *(MR)*: the truck *"R_TRK"* was defined as the *MR* and hence specified as a work flow. The quantity was defined as one as only one truck would be requested for each delivery based on the quantity of steel recycling rate.

Facilitating Resource *(FR)*: the flagman *"FM"* was defined as a *FR* for the activities *Move To Load Stockpiled Steel*, *Load Stockpiled Steel* and *Leave Site*. The backhoe (1 *BH_G*) was defined as a facilitating resource for the activity *Load Stockpiled Steel*.

Disposable Resource *(DR)*: the Stockpiled Steel *"SP_STL"* was defined as the intermediate product *"DR"* generated from previous work flow *Transportation of Steel and Debris*. The *Steel Recycling* work flow was activated upon accumulation of 25 units of *"SP_STL"*.

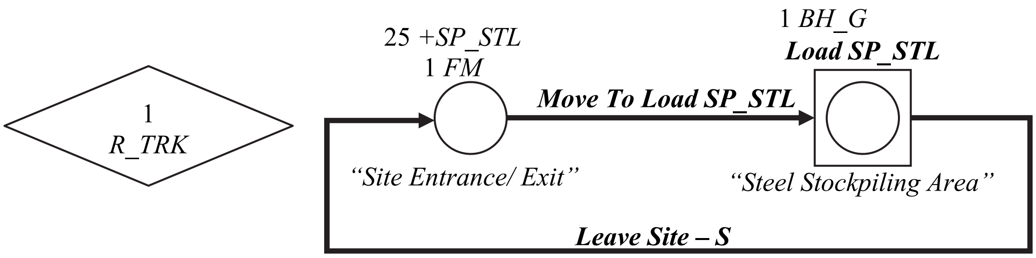


Figure 3.25. Process Mapping Model – Steel Recycling Work Flow

10. Add Disposable Resource Entities

For the simulation model with scale $\frac{1}{40}$ x to the actual project size, 18000 *Raw Demolition Unit* "*R_DU*" was assigned as the initial disposable resource for the project to process. The collection of *Raw Demolition Unit* "*R_DU*" is shown in Figure 3.26, two location circles, "*Demolition Area*" and "*Sorting Area*", were defined in the work flow of *Truck for Raw Demolition Unit* "*TRK_RDU*", with two production activities (i.e. "*Load Demolition Unit*" and "*Unload To Sort*") and two transit activities (i.e. "*Move To Sort*" and "*Return To Demolition*"). A condition for the activity "*Load Demolition Unit*" was set as "*R_DU>0*" (i.e. The amount of *R_DU* at demolition area was greater than zero). Once activity "*Load Demolition Unit*" was finished (i.e. 40 *"R_DU"* were loaded to truck), the control variable was modified as "*R_DU = R_DU - 40*" (i.e. the total amount of *"R_DU"* was deducted by 40 units). For each cycle, 40 units of *Demolition Units "40 DU"* were generated at the end of the activity "*Unload To Sort*" as an intermediate material unit to the sorting process.

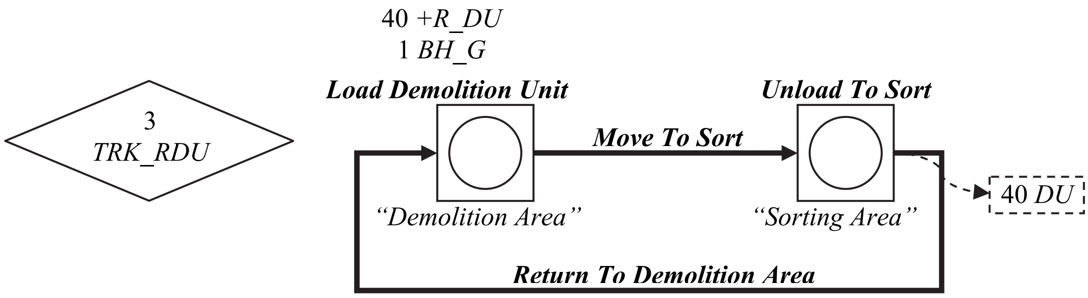


Figure 3.26. Process Mapping Model – Collection of *Raw Demolition Unit*

<u>11. Validate the Model</u>

In order to validate the simulation model, the daily production rate in terms of the quantity of broken concrete being processed was derived from executing a *SDESA* simulation model that closely mirrored site operations and resource provisions as observed in February 2006. Then, the production rate for broken concrete was also obtained from the site record for cross checking the simulation result. Note that site visits were made during February 2006 and the simulation model is supposed to be a close parallel of the actual operation in that month. According to the C&D material report provided by the client, as for February 2006, the total amount of broken concrete produced was 23,653 tons. Given the estimated density of broken concrete of 2.0 ton/m^3 and 24 work days per month, the actual daily production rate for broken concrete was determined as 492.8 m^3 per day. The production rate obtained from the simulation model was averaged 460.8 m^3 per day from one hundred runs of Monte Carlo simulation (the standard deviation was 1.6 m^3 per day). The simulation model was further validated by animation of the demolition processes being simulated in the *SDESA* platform. The animation was able to depict waste handling processes and resource moving patterns that resembled the actual site operation. The simulation graphical output can be shown on the *SDESA* layout for visual validation of the process mapping model and visual inspection of system optimization and scenario analysis.

The actual production rate of 7.71 unit/min was found on-site. The simulation of the models with scale $\frac{1}{160}$ x, $\frac{1}{40}$ x and $\frac{1}{10}$ x to the actual project size gave nominal production rates of 8.77, 9.55 and 9.73 unit/min respectively and meet the target requirement. The order of magnitude of the model production rate is comparable with the actual production rate. Figure 3.27 shows the broken concrete production rate against simulation time for scale $\frac{1}{40}$ x model. The mean production rate is 9.55 unit/min.

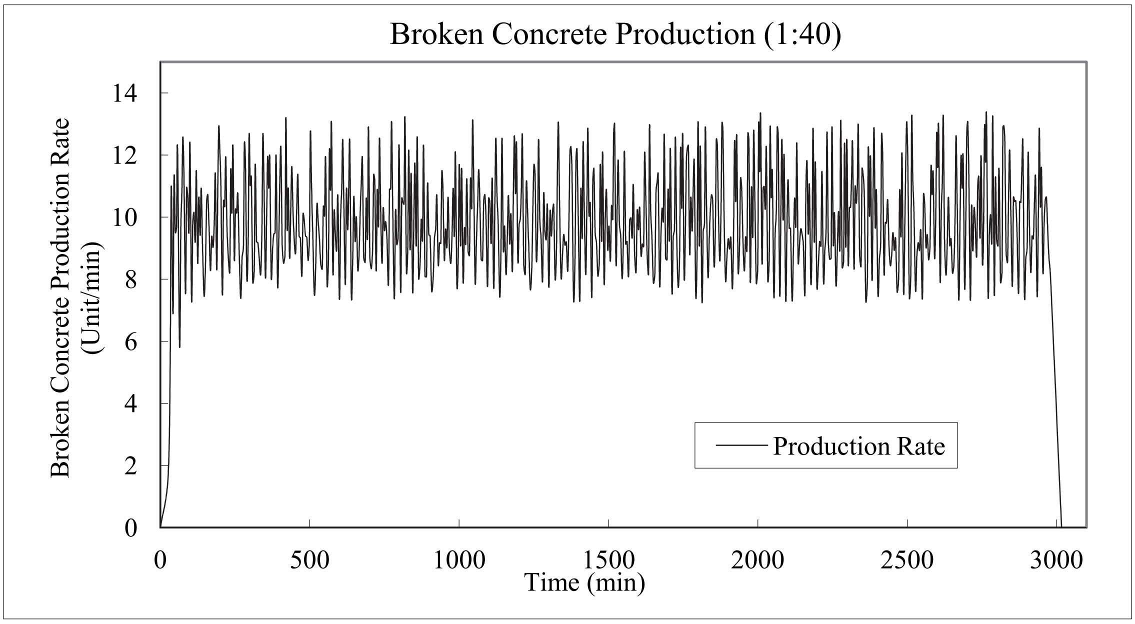


Figure 3.27. Broken Concrete Production Rate against Time for Scale $\frac{1}{40}$ x Model

The flexibility of *SDESA* platform facilitates the discretization and the integration of the simulation model. When work flows and activities from the sub-models are integrated together, the resource pool can be shared with each other with minimal modification.

Observation on the model outputs is also essential for the model validation. Model outputs include animated simulation output for visual inspection of logistical sequences, activity bar chart showing the phases and activities of a project work breakdown structure (WBS) similar to Gantt chart, activity reports expressing the waiting time and activity durations, and resource reports demonstrating the working time of the resources on different activities and idling time.

12. Refine the Model

Resource Transit Information System: the *Bulldozer (BDZ)* was shared between the activities *Grade Large Broken Concrete* and *Grade Small Broken Concrete*. The *Backhoe_General (BH_G)* was served for two activities – *Load Stockpiled Debris* and *Load Stockpiled Steel*. As shown in Table 3.14, *RTIS* states the transition duration for the resources moving between different locations.

Table 3.14. *RTIS* in Kai Tak Airport Demolition Project

Resource	From	To	Transit Duration (min)
BDZ	KT-Small BC Stockpile	KT-Large BC Stockpile	0.5
BDZ	KT-Large BC Stockpile	KT-Small BC Stockpile	0.5
BH_G	KT-Debris Stockpile	KT-Steel Stockpile	0.2
BH_G	KT-Steel Stockpile	KT-Debris Stockpile	0.2

13. Review the Model

Activity Interruptions on activities "Move To Landfill" and "Return To Site" represent trucks moving back and forth between the landfill and the site, subject to traffic jams. To incorporate the effect of traffic jams, a 0.1 (10 percent) probability of occurrence was imposed and the delay time was sampled from a uniform distribution ranging from 10 to 20 minutes. That means on the two transit activities, one out of ten trucks would experience 10 to 20 min added travel time due to traffic jams.

14. Convert the Process Mapping Model to a Simulation Model

Figure 3.28 shows the *SDESA* model of Collection of Raw Demolition Unit work flow

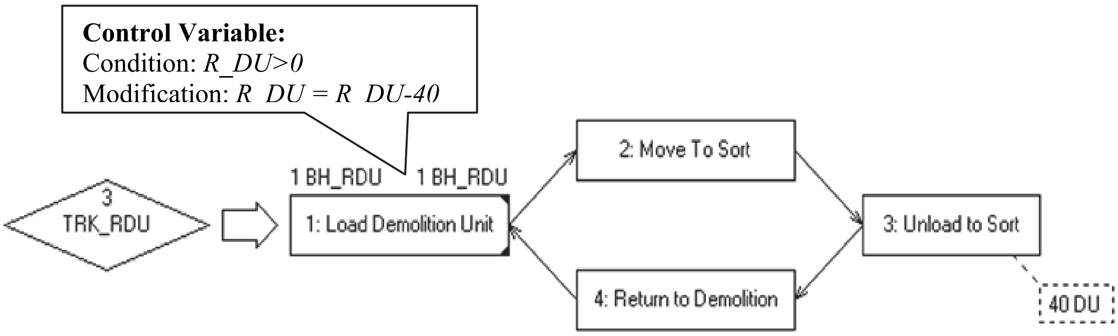


Figure 3.28. *SDESA* Model – *Collection of Raw Demolition Unit* Work Flow

Based on the process mapping model shown in Figure 3.19, the *SDESA* model of *Sieving* Work Flow is established as shown in Figure 3.29.

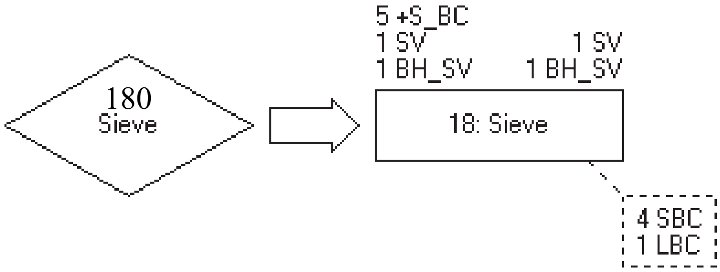


Figure 3.29. *SDESA* Model – *Sieving* Work Flow

The process mapping model of *Steel Recycling* Work Flow given in Figure 3.25 is converted to the *SDESA* model as shown in Figure 3.30.

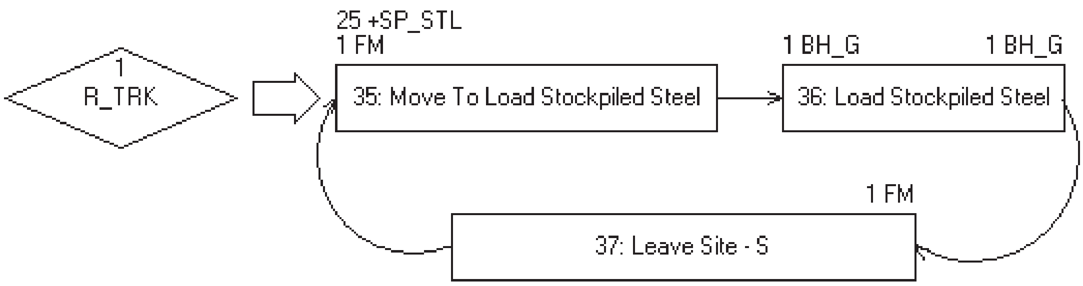


Figure 3.30. *SDESA* Model – *Steel Recycling* Work Flow

Refer to the process mapping model of *Transportation of Steel and Debris* work flow as shown in Figure 3.21, the *SDESA* model is developed as shown in Figure 3.31.

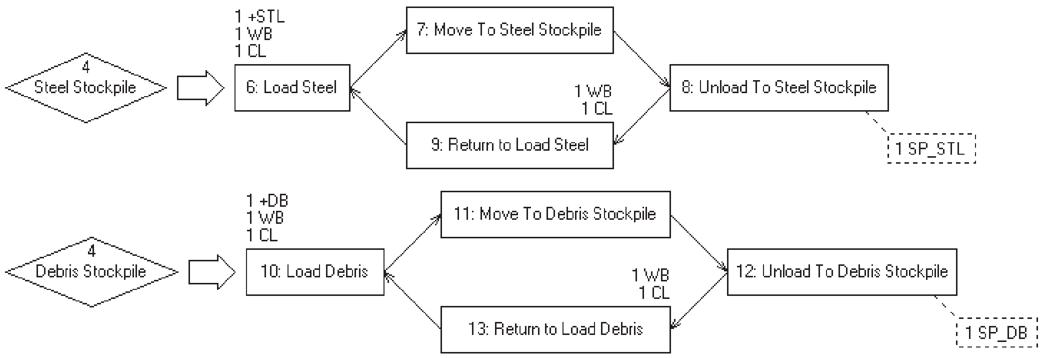


Figure 3.31. *SDESA* Model – *Transportation of Steel and Debris* Work Flow

Figure 3.32 shows the additional transit information of *FR's* in *RTIS* of simulation model.

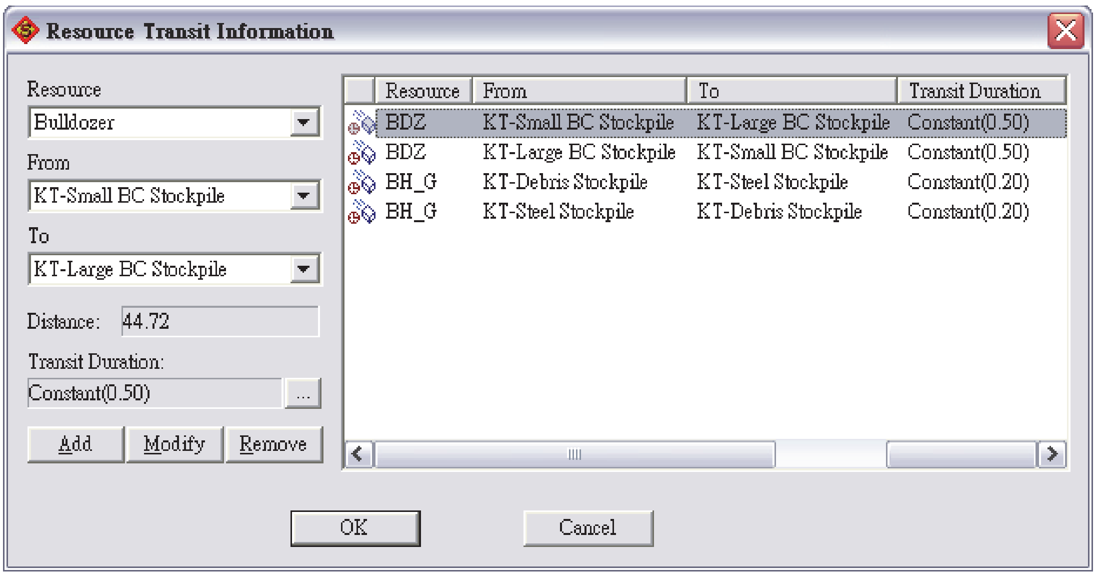


Figure 3.32. Additional Transit Information of *FR's* in *RTIS* of Simulation Model

Figure 3.33 shows a screenshot of the animated simulation output for visual inspection of logistical sequences.

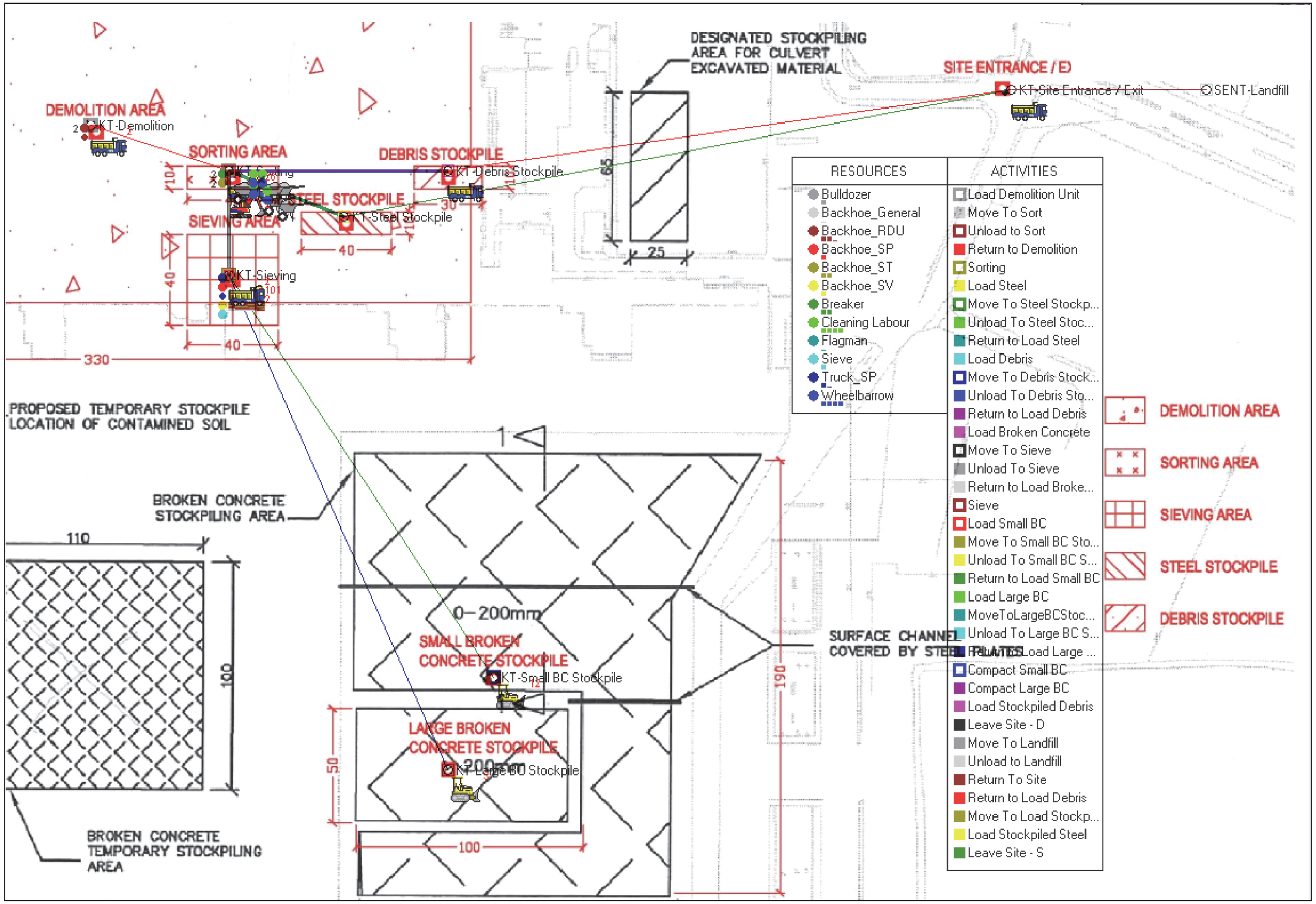


Figure 3.33. Screenshot of the Animated Simulation Output

Figure 3.34 shows the model outputs on activity duration and resource utilization statistics. Problems can be identified through prolonged waiting / idling of some of the resources, unusual utilization rates of the resources or bar chart output showing the activity sequences like the Gantt chart.

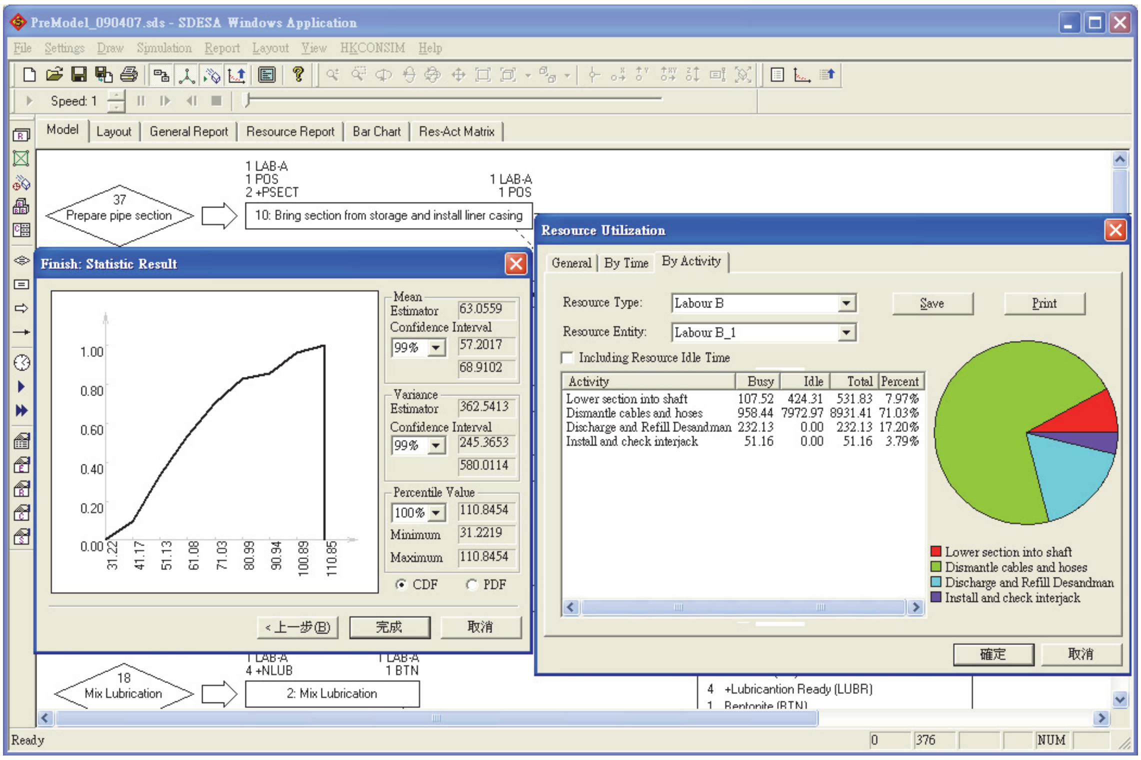


Figure 3.34. Screenshot of *SDESA* Model Outputs on Activity Duration and Resource Utilization Statistics

3.8 Process Mapping Model: Case of Microtunneling Project in Hong Kong

The formal framework for simulation approach and process mapping model is applied to a case study of So Kwun Wat microtunneling project in Hong Kong. The computer application of the framework will be discussed in Chapter 5.

1. Define Simulation Objectives

The study targets at establishing a general algorithm for microtunneling operation simulation modeling approach and streamlining the site operations during the construction of utility tunnels.

2. Define the Scope of Process Mapping Model

Geographical boundary of the model was defined as the site boundary of the microtunneling site, with the pipe delivery route from the remote pipe storage site. The process mapping model includes 1) pipe delivery from the remote site, 2) lower the pipe section to the shaft, 3) jack pipe section and 4) spoil disposal.

On the other hand, the trucks for spoil disposal were not operated under the Contractor. Only scheduling of spoil disposal was concerned about, whereas the subsequent spoil delivery activities were out of scope of the site management system and could be ignored in site layout planning and process mapping model. The spoil disposal activities were condensed to a single activity in the simulation model.

3. Collect Project Data

This research takes advantage of a twin tunnel project in Hong Kong as a unique "test bed" to implement operations simulation modeling in support of pipe jacking construction planning. The first drive was taken as a "pre-drill" run in order to collect pipe-jacking cycle time data, map the main working processes being applied on-site, and identify the practical constraints posed on the site operations and logistics. From the data plots over the drive length, "jacking cycle" time distributions for different tunnel sections was fitted along the whole tunneling drive. With the development of mutual trust with the industry partners including the clients (Hong Kong and China Gas Company Limited and CLP Power Hong Kong Limited), consultant (Black & Veatch) and contractors (Kum Shing Construction Company Limited and Reliance-Tech Limited, a subsidiary of Chun Wo Development Holding Limited), this microtunneling site was adopted as a perfect field laboratory for the framework of process mapping model and its validation.

4. Outline Site Layout and Key Locations

The site layout plan of the So Kwun Wat microtunneling project is shown in Figure 3.35. Key locations in the site space are circled as location circles in the mapping process and listed in Table 3.15.

Table 3.15. Key Locations of So Kwun Wat Microtunneling Project

Site	Location
Remote Storage	Remote Storage
Site	Site Storage
Site	Shaft (Top)
Site	Shaft (Bottom)
Site	Tunnel
Site	Bentonite Storage
Site	Spoil Storage

Figure 3.35. Site overview of So Kwun Wat Microtunneling Project

5. Specify Model Assumptions

For this particular site located at a rural area, the site area was substantially large that plenty of pipe sections could be accommodated on-site.

Learning period was expected for the site establishment and the site operators to become familiar with the site conditions, tunnel alignment control and calibration of the subsidiary systems. The first two cycles for launching the micro TBM head and tail components were omitted from the operation data.

For the first drive, the micro TBM drove across highly varying geological conditions between Chainage (Ch.) 6m and 40m. A uniform sandy soil stratum existed from Ch. 40m to 105m, whereas hard materials were encountered between Ch. 105m to 220m. The cutter discs were found gradually deteriorating during the drive with two major maintenance operations carried out at Ch. 188m and 191m respectively for repairing the micro-TBM to an acceptable state before it can further proceed to the receiving pit at a reduced speed. The site operation data was chosen from Ch. 6m (pipe section No.1) up to Ch. 182m (pipe section No.58).

For the second drive, the micro TBM drove across a uniform silty soil stratum between Ch. 6m to 112m apart from some rocks encountered from Ch. 22m to 24m. Hard materials were found between Ch. 112m to 220m. The site operation data was chosen from Ch. 6m (pipe section No.1) up to Ch. 199m (pipe section No.63).

6. Determine Flow Entities

In the So Kwun Wat microtunneling project, major work flows were identified and their corresponding work units are listed in Table 3.16.

Table 3.16. Work Flows and their Corresponding Work Units in So Kwun Wat Microtunneling Project

Work Flow	**Basic Model Structure (Vehicle Loop (V) / Production Line (P))**	**No. of Work Units**	**Disposal Resources Required**	**Disposal Resources Generated**
Pipe Delivery	P	18	4 *Pipe Delivery*	4 *Pipe Arrival*
Unload Pipe Section	P	72	1 *Pipe Arrival*	1 *Pipe at Storage*
Crane	V	1	1 *Pipe at Storage*	1 *Read to Jack*
Jack Pipe	P	74	1 *Read to Jack*	1 *Need Interjack* 1 *Need Lubrication*
Install Interjack	P	4	16 *Need Interjack*	1 *Interjack Ready*
Mix Lubrication	P	18	4 *Need Lubrication*	4 *Lubrication Ready*
Empty spoil tank	P	18	4 *Spoil Tank Full*	4 *Spoil Tank Not Full*
Discharge and Refill Desandman	P	18	4 *Desandman Ready To Discharge*	4 *Water Ready*
Pipe Truck to Remote Storage	P	18	4 *Spoil Truck*	1 *Pipe Truck at Remote Storage*

Table 3.17 shows the location boundaries of work flows.

Table 3.17. Location Boundaries of Work Flows in So Kwun Wat Microtunneling Project

Work Flow	**Location Boundaries**	
	Location 1	**Location 2**
Pipe Delivery	Remote Storage	Site Storage
Unload Pipe Section	Site Storage	-
Crane	Site Storage	Shaft (Bottom)
Jack Pipe	Shaft (Bottom)	Tunnel
Install Interjack	Shaft (Bottom)	Tunnel
Mix Lubrication	Bentonite Storage	-
Empty spoil tank	Spoil Tank	-
Discharge and Refill Desandman	Spoil Tank	-
Pipe Truck to Remote Storage	Site Storage	Remote Storage

7. Determine the Activities in Work Flows

Activities comprising each work flow along with activity times in the form of uniform distributions or constants are summarized in Table 3.18.

Table 3.18. Activity Definitions of So Kwun Wat Microtunneling Project

Work Flows	Activities	Duration Input Model (min)		
		Type	L	U
Pipe Delivery	Pipe delivery to site	Uniform	25	35
Unload Pipe Section	Stockpile pipe section to site storage	Uniform	2	4
Crane	Attach section to crane	Uniform	2	3
	Lift section to position	Uniform	1	2
	Lower section into shaft	Uniform	1	2
	Setup pipe section on guard rail	Uniform	30	60
	Crane returns	Uniform	1	2
Jack Pipe	Jack pipe section	Uniform	25	480
	Dismantle cables and hoses	Uniform	10	30
Install Interjack	Install and check interjack	Uniform	10	15
	Adjust Interjack	Uniform	10	15
Mix Lubrication	Mix Lubrication	Uniform	25	35
Empty spoil tank	Empty spoil tank	Uniform	20	35
Discharge and Refill Desandman	Discharge and Refill Desandman	Uniform	10	15
Pipe Truck to Remote Storage	Pipe truck return to remote storage	Uniform	15	25

8. Combine the Flow Entities with the Work Flows (Activity Chains)

Refer to the *Pipe Delivery* work flow, the Activity *Pipe delivery to site* was initiated by the available *Pipe Delivery "PDEL"*. The activity would stop only when eighteen *Pipe Delivery* had been processed. Figure 3.36 shows the process mapping model of *Pipe*

Delivery work flow.

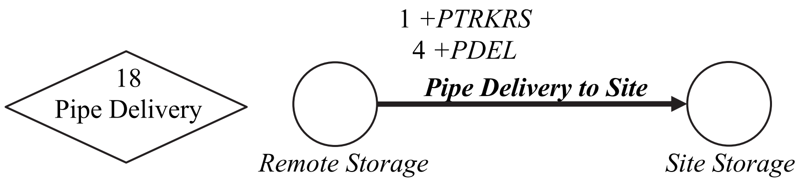


Figure 3.36. Process Mapping Model – *Pipe Delivery* Work Flow

9. Allocate Resources on Activities

Different types of resources are defined in Table 3.19.

Table 3.19. Resource Pool for So Kwun Wat Microtunneling Project

Resource Class	Resource Type	Code	Amount
Moving Resources (MR)	Crane	Crane	1
Facilitating Resources (FR)	Backhoe	BH	1
	Bentonite	BTN	1
	Jacking System	JACK	1
	Labour A	LAB-A	1
	Labour B	LAB-B	1
	Pipe Truck	PTRK	1
	Supervisor	SPV	1
	Spoil Truck	SPTRK	1
Disposable Resources (DR)	Cable, hose, laser Ready	CHLR	1
	Crane Control	CRNC	1
	Desandment Ready to Discharge	DMRTD	0
	Interjack Ready	IJR	0
	Lubrication Ready	LUBR	4
	Need Interjack	NIJ	0
	Need Lubrication	NLUB	0
	Pipe Arrival	PARR	0
	Pipe Delivery	PDEL	4
	Pipe at Storage	PSTOR	2
	Pipe Truck Return	PTRKR	0
	Pipe Truck at Remote Storage	PTRKRS	1
	Ready to Jack	RTJ	0
	Stroage Vacancy	STORV	4
	Spoil Tank Not Full	SPTNF	4
	Spoil	SPOIL	0
	Spoil Tank Full	SPTF	0
	Water Ready	WATR	4

10. Add Disposable Resource Entities

For the each of the tunnel drive, four *Pipe Delivery (PDEL)* were assigned as the initial disposable resources for the project to process. The process mapping model of *Pipe Delivery* work flow in is shown in Figure 3.37, two location circles, "*Remote Storage*" and "*Site Storage*", are defined in the work flow of *Pipe Delivery*, with one transit activity *Pipe delivery to site*. Four *Pipe to Delivery (PDEL)* were delivered from remote storage to site storage. For each delivery, four *Pipe Arrival (PARR)* were generated at the end of the activity *Pipe delivery to site* as a signal to *Unload Pipe Section* work flow.

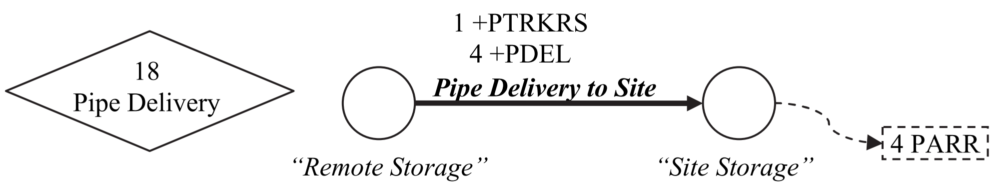


Figure 3.37. Process Mapping Model – *Pipe Delivery* Work Flow with *DR*

11. Validate the Model

This research takes advantage of a twin tunnel project in Hong Kong as a unique "test bed" to implement operations simulation modeling in support of pipe jacking construction planning. The first drive was taken as a "pre-drill" run in order to collect pipe-jacking cycle time data, map the main working processes being applied on-site. The second drive was validated through site visits and records. Working closely with industry partners, this microtunneling site provides a perfect field lab for simulation modeling and verification.

12. Refine the Model

The simulation model is fine-tuned based on the actual site layout plan and estimated activity durations. Further site constraints such as the installation of a number of intermediate jacking stations for reducing total jacking force and machinery breakdown are defined in the model.

13. Review the Model

Further simulation updating is necessary to assisting the construction planner in continuously revising the tentative completion date based on site information gathered. Once the model inputs are updated, the simulation experiments are conducted again to determine the remaining project duration and allocate the resources to synchronize system components. The simulation model was established during the first run, site information was collected for reviewing the model.

14. Convert the Process Mapping Model to a Simulation Model

The process mapping model of *Pipe Delivery* work flow shown in Figure3.37 was converted to the *SDESA* model as shown in Figure 3.38.

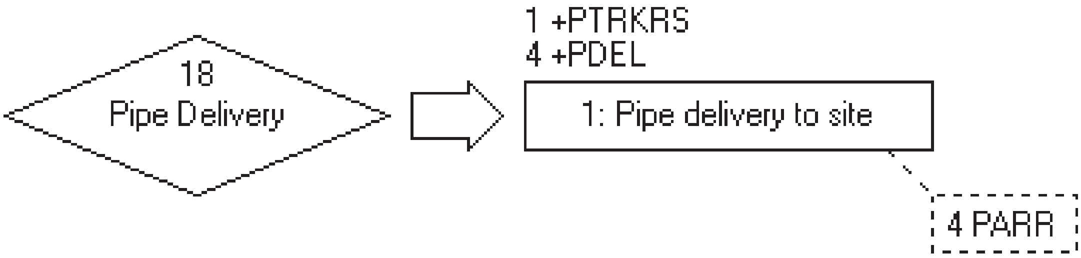


Figure 3.38. *SDESA* Model – *Pipe Delivery* Work Flow

The site layout setting as defined as the location circles is shown in Figure 3.39. The key locations include the remote storage, site storage, top and bottom of the shaft and tunnel.

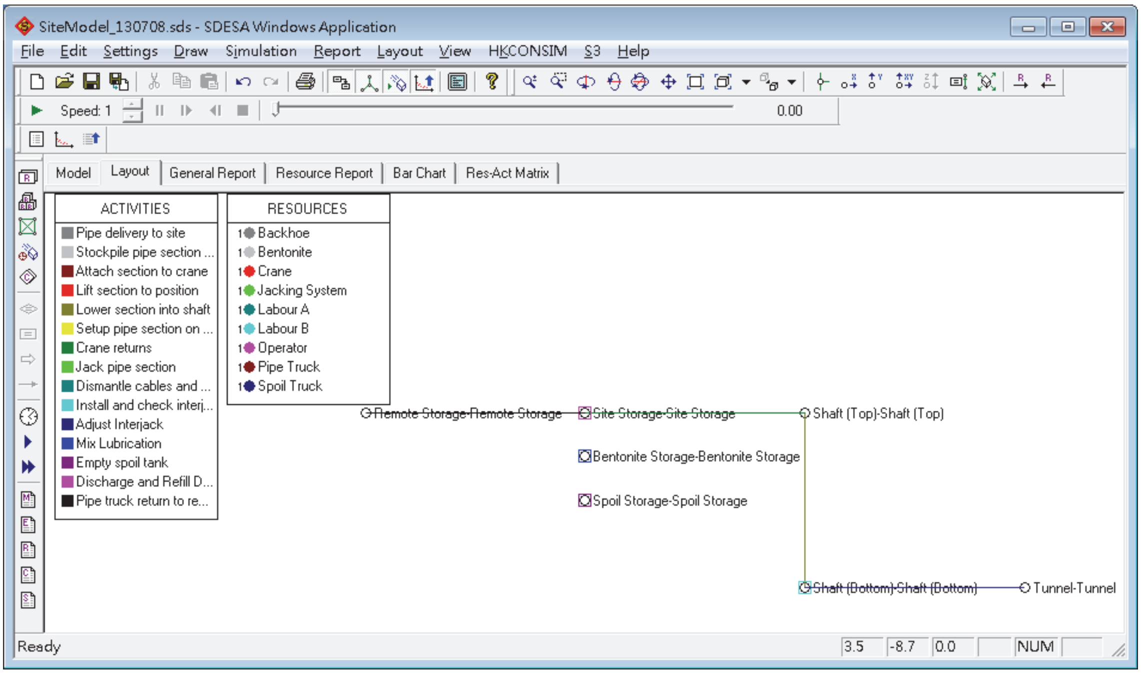


Figure 3.39. *SDESA* Model – Site Layout Setting

Figure 3.40 shows the statistical output on resource utilization for individual resources. Based on the simulation results, the utilization rate of resources can be assessed to streamline the whole production processes.

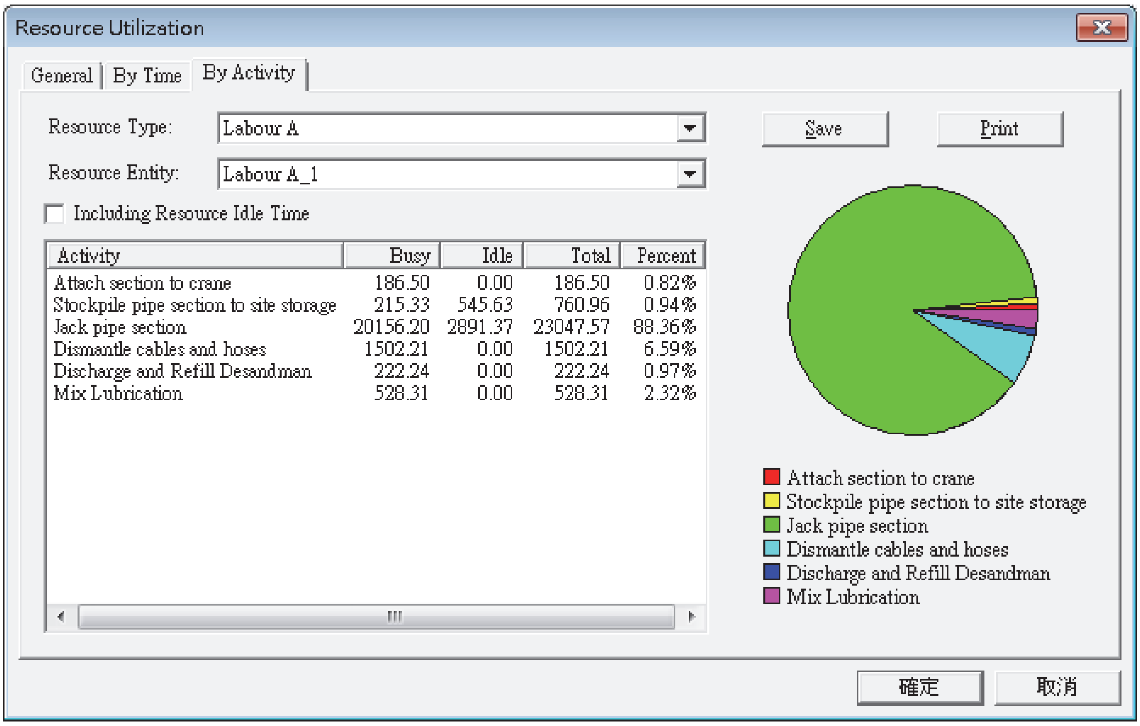


Figure 3.40. Statistical Output on Resource Utilization

3.9 Process Mapping Model: Case of Mining Project in Indonesia

The formal framework for simulation approach and process mapping model is applied to a case study of Indonesian mining project. The computer application of the framework will be discussed in Chapter 7.

1. Define Simulation Objectives

The mining company initiated a trial run of 1.5% of the whole project to try out the plant, machines and crew size, and to optimize the configuration of major resources and processes. The trial run lasted for a year, preceding the 10-year span for the whole mining operation. Throughout the trial run period, simulation experiment was also carried out to supplement the decision making in the actual site management.

2. Define the Scope of Process Mapping Model

The iron sand production resembles earth-moving operations in heavy construction and consists of five main processes: 1) the production of raw sand at the iron ore digging area, 2) the transportation of raw sand from the digging area to the processing plant by trucks (about 1 km travel distance), 3) the magnetic separation of raw sand into iron sand, waste stone, and waste sand by the processing plant, 4) the waste handling operations by loaders, and 5) the transportation of iron sand from the processing plant to the sea port by trucks (about 60 km away). Simulation time was adopted as the production of one barge load.

3. Collect Project Data

The model was set up based on the interview with the site manager. Site information and observations was obtained throughout the interview.

4. Outline Site Layout and Key Locations

The site layout plan of the Indonesian mining project was obtained. The site activities traveling among different locations were observed to valid the site operations. The key locations in the site space were defined as location circles in the mapping process and listed in Table 3.20.

Table 3.20. Key Locations of Mining Project in Indonesia

Site	**Location**
Ore	Digging Area
Processing Plant	Entrance/Exit
Processing Plant	Feeder Box - Start
Processing Plant	Feeder Box - Finish
Processing Plant	Product Output
Processing Plant	WStone Channel
Processing Plant	WM Channel
Processing Plant	Magnetic Separator
Processing Plant	Temp Drying Box
Processing Plant	Stockpile
Processing Plant	WStone Storage
Processing Plant	WM Storage
Processing Plant	WM Embarkment
Port	Stockpile
Port	Barge
Port	Mother Vessel
Port	Destination

5. Specify Model Assumption

During the trial run, the overall target production rate of iron sand was set to be 50,000 ton per month (i.e. 140 ton per hour). The target production rates for four main production flows, namely, raw sand segregation; iron sand processing; stone processing;

fine waste processing, were subsequently inferred by factoring relative densities and material composition.

6. Determine Flow Entities

The iron sand production resembles earth-moving operations in heavy construction and consists of five main processes: 1) the production of raw sand at the iron ore digging area, 2) the transportation of raw sand from the digging area to the processing plant by trucks (about 1 km travel distance), 3) the magnetic separation of raw sand into iron sand, waste stone, and waste sand by the processing plant, 4) the waste handling operations by loaders, and 5) the transportation of iron sand from the processing plant to the sea port by trucks (about 60 km away).

Major work flows are identified and their corresponding work units are listed in Table 3.21.

Table 3.21. Work Flows and Their Corresponding Work Units in Mining Project in Indonesia

Work Flow	**Basic Model Structure (Vehicle Loop (V) / Production Line (P))**	**No. of Work Units**	**Disposal Resources Required**	**Disposal Resources Generated**
Transport to Processing Plant	V	10	19 *ORE1*	19 *ORE2*
Processing	P	1880	19 *ORE2*	4.13 *ORE4* 7.44 *WStoneF* 7.44 *WM_F*
Waste Stone Flow	P	1880	7.44 *WStoneF*	7.44 *SP_WStone*
Waste Material Flow	P	1880	7.44 *WM_F*	7.44 *SP_WM*
Ore Flow	P	1880	4.13 *ORE4*	4.13 *ORE5*
Truck to Temp Dry Box	V	1	27.5 *ORE5*	27.5 *ORE6*
Truck to Site Stockpile	V	1	27.5 *ORE6*	27.5 *ORE7*
Call Port Truck	P	1	-	280 CPT
Truck to Port Stockpile	V	25	27.5 *ORE7*	27.5 *ORE8*
Truck to Berth	V	1	27.5 *ORE8*	27.5 *ORE9*
Barge	V	1	7700 *ORE9*	7700 *ORE10*
Waste Dump Request	P	8	-	250 *WSDR* 250 *WMDR*
Waste Stone Dumping	V	1	17.5 *SP_WStone*	17.5 *DWM*
Waste Material Dumping	V	1	17.5 *SP_WM*	17.5 *DWM*
Embankment Construction	P	1600	17.5 *DWM*	17.5 *WD*

Table 3.22 shows the location boundaries of work flows.

Table 3.22. Location Boundaries of Work Flows in Mining Project in Indonesia

Work Flow	**Location Boundaries**	
	Location 1	**Location 2**
Transport to Processing Plant	Ore-Digging Area	PP-Feeder Box - ST
Processing	PP-Feeder Box - ST	PP-Feeder Box - FN
Waste Stone Flow	PP-Magnetic Separator	PP-WStone Channel
Waste Material Flow	PP-Magnetic Separator	PP-WM Channel
Ore Flow	PP-Magnetic Separator	PP-Product Output
Truck to Temp Dry Box	PP-Product Output	PP-Temp Drying Box
Truck to Site Stockpile	PP-Temp Drying Box	PP-Stockpile
Call Port Truck	PP-Stockpile	-
Truck to Port Stockpile	PP-Stockpile	Port-Stockpile
Truck to Berth	Port-Stockpile	Port-Barge
Barge	Port-Barge	Port-Mother Vessel
Waste Dump Request	PP-WStone Storage	-
Waste Stone Dumping	PP-WStone Storage	PP-WM Embankment
Waste Material Dumping	PP-WM Channel	PP-WM Embankment
Embankment Construction	PP-WM Embankment	PP-WM Embankment

7. Determine the Activities in Work Flows

Activities comprising each work flow along with activity times in the form of uniform distributions or constants are summarized in Table 3.23.

Table 3.23. Activity Definitions of in Mining Project in Indonesia

Work Flows	Activities	Mean Duration (min)
Transport to Processing Plant	Load 1st Ore	5
	Transport to Entrance	3
	Transport to Feeder Box	2.4
	Unload to Feeder Box	1.8
	Travel to Exit	1.8
	Return to Raw Ore	2
Processing	Processing	3.6
Waste Stone Flow	Waste Stone Flow	9
Waste Material Flow	Waste Material Flow	9
Ore Flow	Ore Flow	9
Transport to Temp Drying Box	Load 5th Ore	2
	Transport to Temp Drying Box	0.3
	Unload to Temp Drying Box	1
	Return to Product Output	0.2
Transport to Site Stockpile	Load 6th Ore	2
	Transport to Site Stockpile	0.5
	Unload to Site Stockpile	1
	Return to Temporary Drying Box	0.4
Transport to Port Stockpile	Load 7th Ore	2
	Transport to Exit	0.6
	Transport to Port Stockpile	156
	Unload to Port Stockpile	1
	Return to Entrance	130
	Return to Site Stockpile	0.5
Transport to Berth	Load 8th Ore	2
	Transport to Berth	0.6
	Unload to Berth	1
	Return to Port Stockpile	0.4
Transport to Mother Vessel	Load 9th Ore	0
	Transport to Berth	30
	Unload to Berth	10
	Return to Port Stockpile	20
Waste Stone Dumping	Load Waste Stone	2
	Transport Waste Stone to Waste Material Embankment	0.7
	Unload Waste Stone to Waste Material Embankment	0.8
	Return to Waste Stone Storage	0.6
Waste Material Dumping	Load Waste Material	2
	Transport Waste Material to Waste Material Embankment	0.7
	Unload Waste Material to Waste Material Embankment	0.8
	Return to Waste Material Storage	0.6
Embankment Construction	Embankment Construction	4

8. Combine the Flow Entities with the Work Flows (Activity Chains)

In the *Transport to Processing Plant* work flow, the Activity *Load 1st Ore* was initiated by the available *raw ore "ORE_1"*, i.e. *"ORE_1 >0"* (When there existed "*ORE_1"* at the mining site). The activity would stop only when all the pre-defined number of "*ORE_1"* had been processed.

9. Allocate Resources on Activities

Different types of resources are defined in Table 3.24.

Table 3.24. Resource Pool for Mining Project in Indonesia

Resource Class	Resource Type	Code	Amount
Moving Resources(MR)	Truck to Processing Plant	TRK_PP	10
	Truck to Temp Dry Box	TRK_TDB	1
	Truck to Site Stockpile	TRK_SS	1
	Truck to Port Stockpile	TRK_PS	25
	Truck to Berth	TRK_B	1
	Barge	BAR	1
	WStone Dumping	WSD	1
	WM Dumping	SMD	1
Facilitating Resources (FR)	Backhoe-Dig	BH-DIG	4
	Bulldozer	BDZ	2
	Feeder Box	FBOX	1
	Loader-Feeder Box (WA 350)	WA 350	1
	Loader-Output (Kamatsu PC 200)	PC 200	1
	Loader-Temp Drying Box	LD-TDB	1
	Loader-Site Stockpile	LD-SSP	1
	Loader-Port	LD-PORT	1
	Loader-WStone	LD-WS	1
	Loader-WM	LD-WM	1
	Magnetic Separator-WS	MS-WS	1
	Magnetic Separator-WM	MS-WM	1
Disposable Resources (DR)	Raw Ore	ORE_1	35750
	Ore Unloaded to Feeder Box	ORE_2	0
	Separated Ore to Feeder Box End	ORE_3	0
	Ore to Magnetic Separator	ORE_4	0
	Ore to Sedimentary Tank	ORE_5	0
	Ore to Temporary Drying Box	ORE_6	0
	Ore to Site Stockpile	ORE_7	0
	Ore to Port Stockpile	ORE_8	0
	Ore to Barge	ORE_9	0
	Ore to Mother Vessel	ORE_10	0
	Waste Stone	WStone	0
	Waste Stone Flow	WStone_F	0
	Waste Stone at Channel	WStone_C	0
	Waste Material	WM	0
	Waste Material Flow	WM_F	0
	Waste Material at Channel	WM_C	0
	Dump Waste Material	DWM	0
	Waste at Embankment	WD	0

10. Add Disposable Resource Entities

For the simulation model with one barge load production, 35750 *Raw Ore (ORE_1)* was assigned as the initial disposable resource for the project to process. The *Transport to Processing Plant* work flow is shown in Figure 3.41.

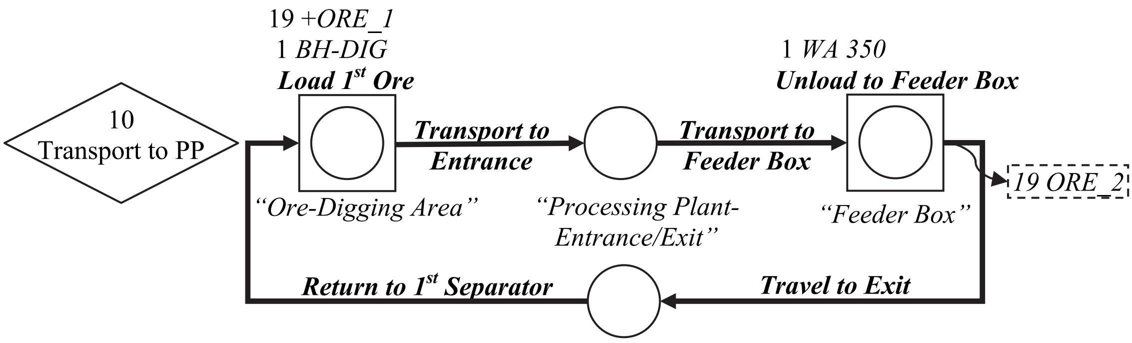


Figure 3.41. Process Mapping Model – *Transport to Processing Plant* Work Flow

Three location circles, *"Ore-Digging Area", "Processing Plant- Entrance/Exit"* and *"Feeder Box"*, were defined in the work flow of *Transport to Processing Plant,* with two production activities (i.e. *Load 1st Ore* and *Unload to Feeder Box*) and four transit activities (i.e. *Transport to Entrance, Transport to Feeder Box, Travel to Exit* and *Return to 1st Separator*).

11. Validate the Model

The model was set up based on the site manager's observation. The simulation results showed a close match between the model and the site production. The target production rate of 50,000 ton per month (140 ton per hour) was reached for the trial production period. The critical resource was the processing plant (feeder box and magnetic separator) from both the model and the site observation.

12. Refine the Model

The magnetic separation plant used in mining operations is identified as a continuous plant. The discrete event model cannot be directly applied to the continuous plant modeling. In tackling the problem, *"pseudo resource entities" (N)* were developed in this research to simulate the continuous nature of the operations in the processing plant. The definition of the *"pseudo resource entities"* will be discussed in Chapter 6 and the application will be discussed in Chapter 7.

13. Review the Model

In additional to intermediate products, cumulative intermediate products were introduced to the model to trace the production rate at different stages and the bottleneck. Particularly, the model was instrumental in advising the mine manager: 1) four backhoe excavators should be made available at the digging area for raw sand excavation; 2) ten trucks (each having a payload of 19 tons) should be deployed for moving the raw sand from the digging area to the processing plant (about 1 km travel distance), and 3) twenty-five trucks were required to transport the iron sand as produced from the processing plant to the port (about 60 km away). The simulation results served as valuable input to design the iron ore production system; in particular, the simulation provided analytical backup to help the mining company streamline the truck fleet, bringing in cost savings in rental and fuel.

<u>14. Convert the Process Mapping Model to a Simulation Model</u>

The process mapping model of *Transport to Processing Plant* given in Figure 3.41 is converted to *SDESA* model as shown in Figure 3.42. A condition for the activity *Load 1^{st} Ore* was set as *"ORE_1>0"* (i.e. the amount of ORE_1 at ore digging area was greater than zero). Once activity *Load 1^{st} Ore* was finished (i.e. 19 ORE_1 were loaded to truck), the control variable was modified as *"ORE_1=ORE_1-19"* (i.e. the total amount of *"ORE_1"* was deducted by 19 units). For each cycle, 19 units of *Ore Unloaded to the Feeder Box "19 ORE_2"* were generated at the end of the activity *Unload to Feeder Box* as an intermediate unit to the ore separation process.

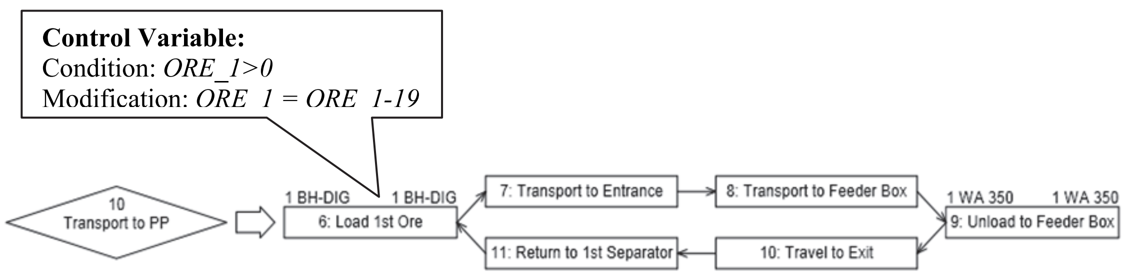


Figure 3.42. *SDESA* Model – Transport to Processing Plant Work Flow

The *Port trucks* were called once a week to deliver the settled iron ore stockpiled at site to the port. The flow entity can be defined by at every seventh day (7 Day x 8 working hours / Day x 60 minutes / hour = 3360 minutes). The arrival time of the *Call Port Truck* work flow is 3360 minutes (after the seventh day). Regular interval of every seven days after the first flow entity is defined by the setting of Interval as "Constant(3360)" minutes as shown in Figure 3.43.

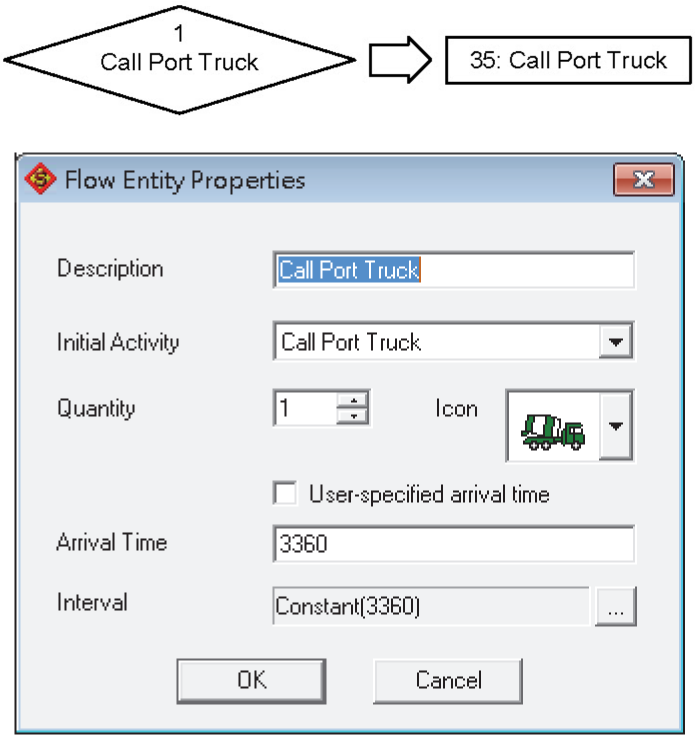


Figure 3.43. Flow Entity Properties for Call Port Truck Work Flow in Mining Project in Indonesia

The simulation output can be observed through animation as shown in Figure 3.44.

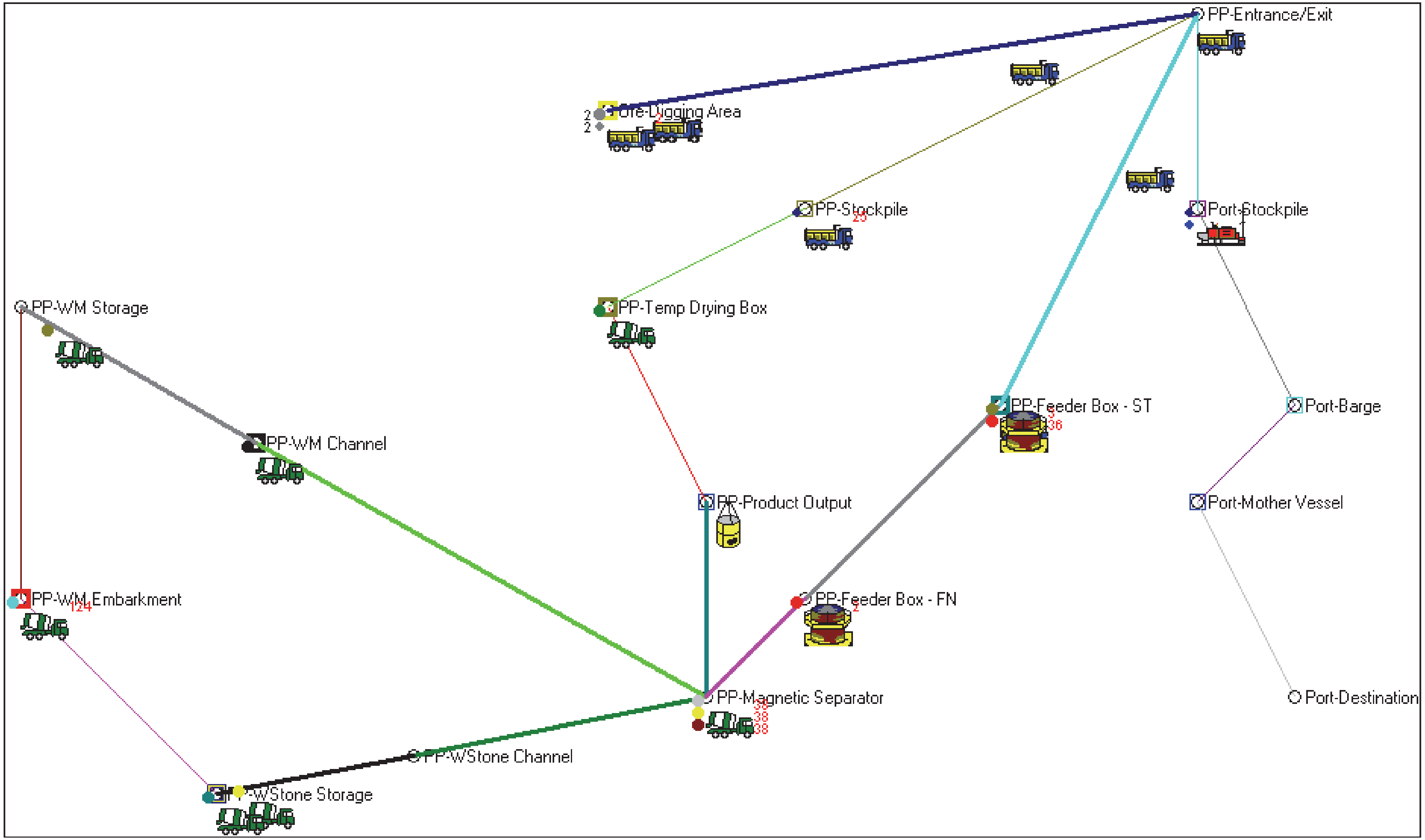


Figure 3.44. Site Layout of Mining Project in Indonesia

3.10 Chapter Summary

The framework for the process mapping and simulation modeling has been formalized. The terminology for simulation modeling and simplified discrete event simulation approach (*SDESA*) adopted in this research has also been defined. The general procedures to establish a process mapping model with a small illustrating road base construction example is given. Three case studies are described for application of the framework for process mapping model. All of the aforementioned processes mapping models are readily convertible into simulation models. The detailed computer application for implementing the framework to each individual case study will be demonstrated in the following chapters.

Chapter 4

Evaluating Cost Efficiency of Selective Demolition Practices: Case of Hong Kong's Kai Tak Airport Demolition

4.1 Introduction

Construction operations and problems can be large in nature. This chapter aims at demonstrating the capability of the proposed formalized simulation modeling method to solve the large systems for C&D waste management.

The remainder of this chapter is organized as follow. The background of the case of waste management of the Kai Tak Airport demolition site and selection demolition is given in Chapter 4.2. The simulation objective is defined in Chapter 4.3. The waste handling process mapping model is converted to *CYCLONE* model and *SDESA* model in Chapter 4.4 and validation of the extended *SDESA* model is shown in Chapter 4.5. The selection of optimum simulation model size is given in Chapter 4.6. The cost efficiency of selective demolition practice is evaluated through scenario analysis in Chapter 4.7. Discussions and conclusions are given in Chapter 4.8.

4.2 Background of Case Study

This case study resorts to the use of proposed framework of simulation approach and process mapping model and was converted to construction operations simulation modeling to investigate the cost efficiency of waste handling practice on the Kai Tak airport demolition project in Hong Kong. By modeling the site operation of sieving and stockpiling broken concrete, the well-established construction simulation methodology of *CYCLONE* was contrasted with the newly developed *Simplified Discrete Event Simulation Approach (SDESA)*. Further, the *SDESA* model was readily extended to include: 1) raw demolition waste collecting and sorting; 2) broken concrete sieving and stockpiling; 3) steel bar recycling and 4) debris disposal at landfill. The production rate derived from simulation was indicative of a close match between the simulation model and the actual site system. The resulting simulation model provided a basis for evaluating the cost efficiency of actual site operations and alternative resource provision scenarios being postulated. Through computer simulation, the actual site operation was found smooth and efficient with utilization rates for resources of different types ranging from 79% to 99%. In addition, the cost-time reduction ratios were calculated for four alternatives of resource provisions in comparison against the original base case. The findings suggested that provided the project budget had satisfied the higher cash flow requirement, doubling the resource provision on site would potentially cut the project duration by half while not increasing the total direct cost.

4.2.1 Selective Demolition

The construction and demolition (C&D) waste consists mainly of concrete, masonry, gravels, metal, and wood, resulting from various types of construction activities including building, demolition, excavation, renovation, formation and road works (Bossink and Brouwers 1996). The C&D waste can be classified into inert and non-inert components (Environment, Transport and Works Bureau 2005). The inert waste refers to non-organic 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 non-inert waste and are largely disposed of at landfills. Demolition of existing structures generally generates ten to twenty times more waste by weight than construction of new buildings (Poon et al. 2001). In redeveloping urban areas, demolition of an existing structure is often required to complete in tight time and cost frames, prior to clearing the site for new construction. As such, the common practice is to remove the demolition waste in its fully mixed state as produced in the first place, resulting in a blend of inert waste with non-inert waste. The contaminated waste materials would require expensive off-site treatment for segregating the reusable portion. As a result, C&D waste handling and recycling is technically and economically difficult (Lawson et al. 2001). In Hong Kong, recycling the mixed C&D waste for reuse in reclamation and site formation projects is basically economically infeasible; instead, the majority of the mixed C&D waste is directly disposed of at landfills (Poon et al. 2004).

Selective demolition is the process of demolishing building components in the reverse order of how they are initially constructed (Guy 2001), which requires considerable on-site sorting efforts to separate the demolition waste for reuse and recycling. According to a trial study of C&D waste recycling (Environment, Transport and Works Bureau 2002), raw demolition waste could be processed into approximately 1) 10% non-inert refuse; 2) 80% inert waste that can be directly reused; and 3) 10% inert waste that requires crushing before being recycled. Nonetheless, economic benefits of selective demolition only materialize if 1) the cost of landfilling is more expensive than that of on-site sorting and transporting waste to recycling facilities; and 2) the price of primary aggregates exceeds that of recycled aggregates (Duran et al. 2005). Municipalities across the world impose C&D waste management regulations in an attempt to increase the recycling rate and the lifetime of existing landfills, for example, implementing the charging scheme based on the polluter-pays principle. In preparing a new bid for an urban redevelopment project , contractors also need to draw up detailed, cost-effective demolition plans, addressing the organization structure of the environmental team, the measures to reduce or minimize generation of C&D waste, on-site sorting, temporary storages, recycling arrangements, record keeping, performance monitoring, and provision of training (Kwong 2003). As workman hours incurred in selective demolition are offset by reduced waste disposal charges at the landfill, the overall demolition cost is estimated to increase only by ten to twenty percent (Lauritezen and Hahn 1992).

4.3 Simulation Objective

In this case study, the use of operations simulation modeling was resorted to investigate the cost efficiency of the selective demolition and waste handling practices on the Kai Tak Airport demolition project in Hong Kong. In particular, modeling the operation of sieving and stockpiling broken concrete was focused on in order to demonstrate the application of proposed framework. First, dynamic work flows are portrayed with the well-established construction simulation methodology of *CYCLONE*. Then, on the same case, an application framework for modeling waste-handling processes is implemented, resulting in fast development of an operations simulation model by *SDESA*. Further, the *SDESA* model is readily extended to cover the entire on-site waste-handling operations. Presented with input settings reflecting the actual site system (activity times and resource provisions), the simulation model yielded a production rate close to actually recorded production performance. Following validation of the base case model, different resource provision scenarios were postulated and further investigated through simulation experiments. The relationships among resource provisions, total direct cost, and total production time were analyzed and the most cost efficient waste management system was identified. Conclusions are drawn and future research enhancements discussed in the end.

4.4 Waste-Handling Process Mapping and Simulation

The operation of the new airport in Hong Kong in 1998 brought the service of the old Kai Tak Airport to closure. The demolition of the Kai Tak Airport began in May 2005 in order to make room for new commercial and residential developments in the city of Hong Kong. Figure 4.1 shows the project layout of the Kai Tak Airport Demolition Project. Input data for Kai Tak Airport simulation were obtained by 1) interviewing engineers of the client, 2) paying site visits, and 3) eliciting relevant project information from site engineers representing both the contractor and the consultant.

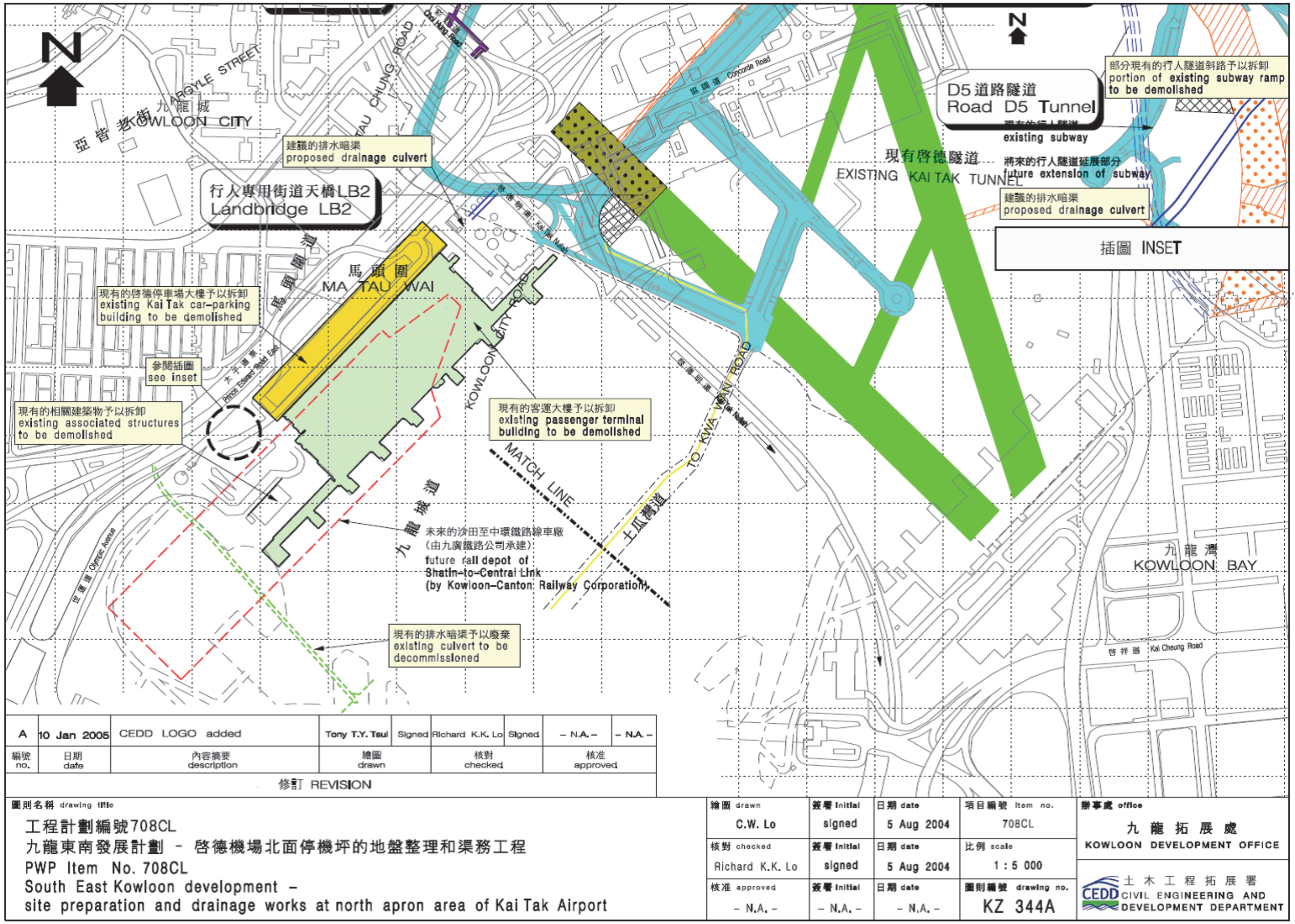


Figure 4.1. Project Layout of Kai Tak Airport Demolition Project

The demolition of the Kai Tak Airport consisted of three consecutive phases, namely, 1) demolition of the terminal building, 2) demolition of the footbridge connecting an adjacent hotel to the multistory car-park building, and 3) demolition of the multistory car-park building. Note that the bulky size and contamination by non-inert waste (e.g. paper, timber, plastics) render direct reuse of broken concrete from demolition unsuitable. In the site, selective demolition was practiced to facilitate the separation and sorting of the demolition waste, resulting in an overall material recycling rate of 90 to 95 percent. Reinforced steel was initially sorted from the concrete and brick debris. Concrete was then crushed, sieved on-site before being transferred to other reclamation sites or off-site C&D material recycling facilities where broken concrete was turned into aggregates of different sizes and recycled products. From the site records, a total volume of 115,400 m^3 broken concrete was produced.

In establishing the simulation models, one unit of waste is assumed, for convenience, to be equivalent to 0.1 m^3 in quantity take-off across multiple work flows. In order to demonstrate the modeling methodologies, it was arbitrarily assumed that 900 units of broken concrete were temporarily stockpiled, which would be segregated into small broken concrete (0-200mm) and large broken concrete (200-400mm) and further trucked to stockpiles at designated areas on the site.

At the temporary stockpile near the sieve location, a *backhoe (BH_SV)* with a bucket of 5 units handled the *broken concrete (BC)* onto a *sieve (SV)*. Hence, a total of 180 bucket loads of *BC* were to be processed. *BC* was then sieved into *small broken concrete (SBC)* and *large broken concrete (LBC)* by a ratio of four to one (4:1) according to the site record. Thus, a total of 900 units of broken concrete would produce 720 units of *SBC* and 180 units of *LBC*, respectively. Upon the accumulation of a truck load of 45 units of either *SBC* or *LBC*, a *backhoe (BH_SP)* −which was exclusively allocated for serving the sieving process− would load the sorted broken concrete into a *truck (TRK_SP)*. The truck then transported the broken concrete to the designated area in the site for stockpiling. The truck returned to the sieving area for another load. Note that 720 units of *SBC* would be transferred in 16 truck loads, whereas 180 units of *LBC* made 4 truck loads. It was observed that two *trucks* (*TRK_SP*) were actually deployed on site. The two work flows of moving *SBC* and *LBC* took place in parallel; roughly, one truck load of *LBC* was handled once four truck loads of *SBC* were processed.

Figure 4.2 shows 1) the overall site layout and operation, and 2) plant around the sieving area.

(a)

(b)

Figure 4.2. (a) Overview of Site Layout and Demolition Operations; (b) Plant Deployed at Sieving Area

Note: BH_ST-Backhoe for Sorting; BH_SV-Backhoe for Sieve; BH_SP-Backhoe for Stockpiling; TRK_SP-Truck for Stockpiling; BC-Broken Concrete; SP_LBC-Stockpiled Large Broken Concrete; SP_SBC-Stockpiled Small Broken Concrete.

4.4.1 CYCLONE Model

Figure 4.3 gives a *CYCLONE* representation for the waste-handling operation described above. The explanation is given as follows:

In the *CYCLONE* model (Figure 4.3), 900 resource entities – each being one unit of broken concrete of mixed sizes – are initialized at the "*BC*" Que node. The function node "*CON 5*" is used to convert the broken concrete into bucket-loads for sieving (5 units broken concrete makes one bucket load.) Execution of the "*Sieve*" Combi activity is contingent on combining three resources, namely, one *BH_SV,* one *SV* and a bucket load of *BC*. After sieving one bucket load of *BC*, 1 unit of *LBC* and 4 units of *SBC* are generated. The function node "*GEN 4*" models the generation of 4 units of *SBC,* whereas the ensuing function node "*CON 45*" accumulates 45 units of *SBC* into one truckload at the "*SBC*" Que node, ready for truck loading. The two Combi nodes − namely, Combi *"Load Small BC"* and Combi *"Load Large BC"* − share the resources of one *BH_SP*, two *TRK_SP*, as initialized at their respective Que nodes. At the end of the two Normal activities *"Unload to Small BC Stockpile"* and *"Unload to Large BC Stockpile"*, a function node "*GEN 45*" converts one truck load into 45 units of *SBC* or *LBC*, which are delivered to the on-site stockpiles designated for *SBC* and *LBC,* respectively, as represented by two Que nodes: "*SP_SBC*" and "*SP_LBC*".

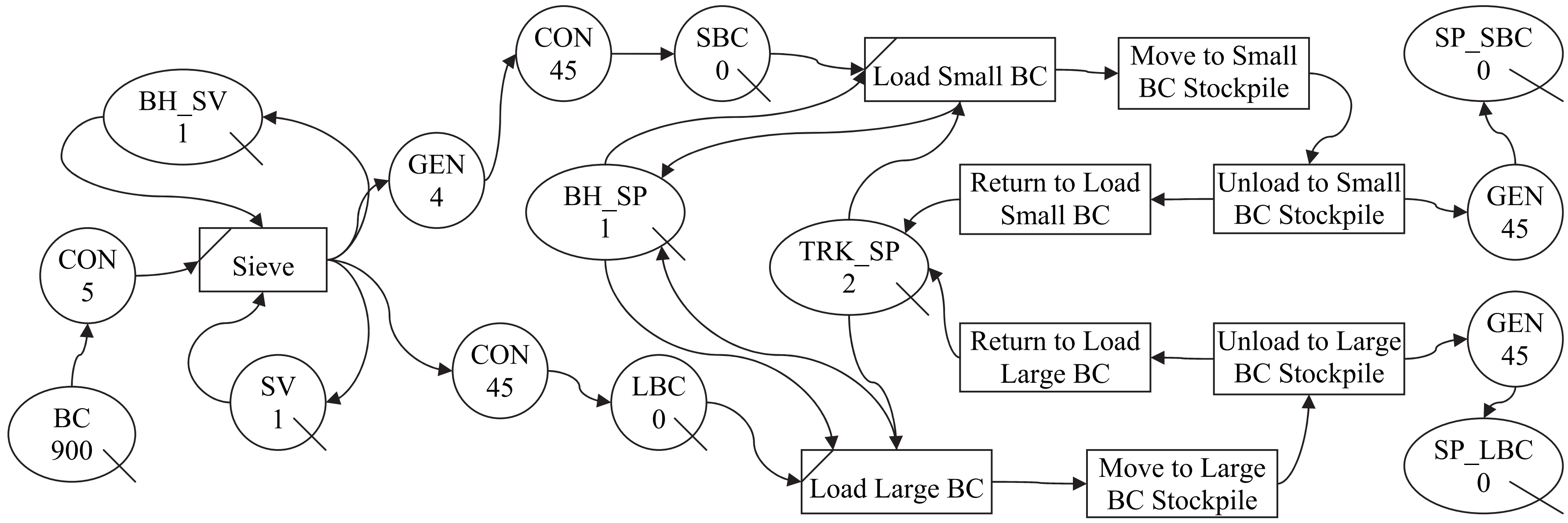


Figure 4.3. *CYCLONE* Model for Sieving and Stockpiling Work Flow

4.4.2 *SDESA* Model

Alternatively, the same case can be tackled by following the application framework specially developed for guiding the mapping and simulation of waste-handling processes (Lu et al. 2006). First, on-site waste flows are traced and mapped with a straightforward process flowchart. Lu et al. (2007a) formalized the connection between the mapping and simulation techniques 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 by *SDESA*. With the simulation model, contractors can readily evaluate and analyze the efficiency and cost effectiveness for a given waste-handling method through computer simulation experiments. (Lu et al. 2009b)

Figure 4.4 gives the process mapping model for the present case, in which the waste processing (shown as an ellipse in Figure 4.4) denotes various waste-handling activities like "loading waste", and "sorting waste". At the top of Figure 4.4, 900 units of *BC* are initialized at a square node (the waste origin), ready for handling. The resource requirements for executing a waste processing are marked at the upper left-hand corner of an ellipse. The start and finish locations of each activity are further linked to the processing activity and tagged at the upper right-hand corner of an ellipse.

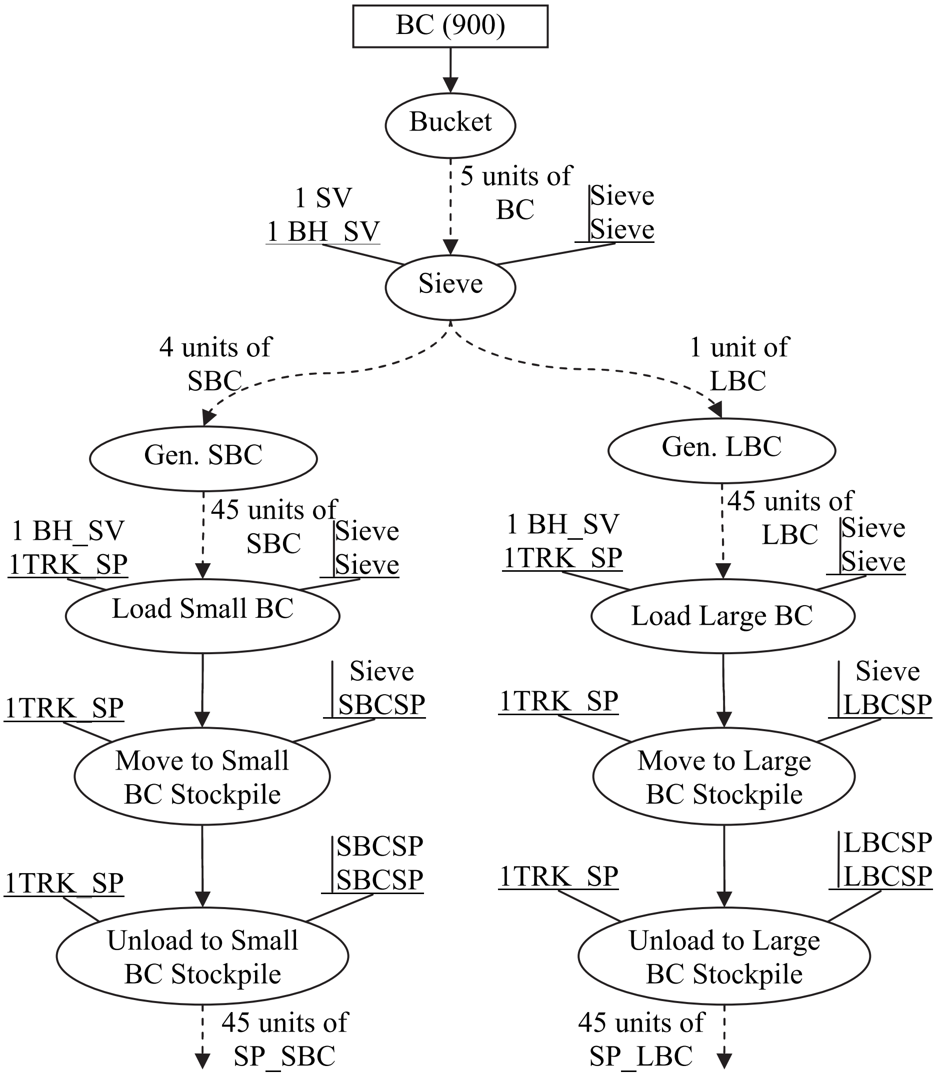


Figure 4.4. Waste-handling Process Flowchart for Sieving and Stockpiling Work Flow

The present case consists of three main work flows; 1) sieving broken concrete; 2) trucking small broken concrete to stockpile; and 3) trucking large broken concrete to stockpile. Dotted arrows are used to portray dependencies between work flows. For example, a dotted arrow connects the *"Sieve"* processing to the *"Gen. SBC"* processing in Figure 4.4, which represents that 4 units of *SBC* are generated after sieving one bucket load of *BC*; the *"Gen. SBC"* connects to *"Load Small BC"* with a dotted arrow, indicating the logic that 45 units of *SBC* convert into one truck load. The operation being modeled involves three key locations at the site, namely, the "*Sieve*" location, the "small broken concrete stockpile" ("*SBCSP*") location, and the "large broken concrete stockpile" ("*LBCSP*") location.

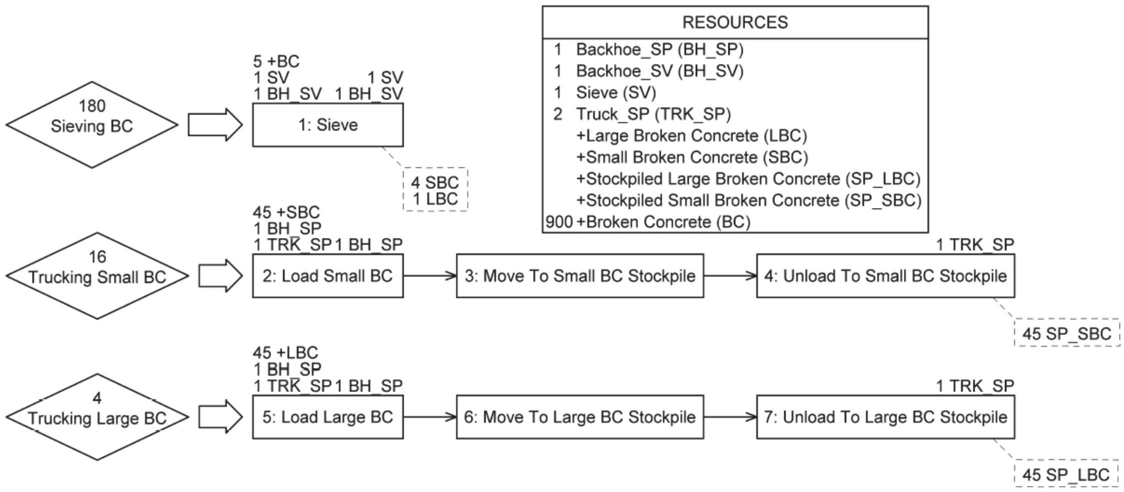


Figure 4.5. *SDESA* Model of Sieving and Stockpiling Work Flow

The resulting *SDESA* simulation model is shown in Figure 4.5, which consists of the three work flows as identified from the previous process mapping. A diamond block preceding the work flow initializes a certain number of flow entities, which will go through logically connected activities forming the work flow. In a *SDESA* simulation model, defining each individual activity entails the specification of activity time, resource requirements, along with start and finish locations. In the present case, 180 bucket loads of *BC*, 16 truck loads of *SBC*, and 4 truck loads of *LBC* are the flow entities to be processed by three work flows, respectively, namely, "*Sieving BC*", "*Trucking SBC*", and "*Trucking LBC*". Resource requirements are marked on the upper left-hand corner of each activity block, whereas at the end of an activity, resources to be released and disposable resources to be generated (which are waste material units prefixed with a plus sign, such as *BC*, *LBC*, and *SBC*) are marked on the upper right-hand and the lower right-hand corner, respectively. Take Activity 1 "*Sieve*", for example, its resource requirements include "*5 +BC*", "*1 SV*", and "*1 BH_SV,*" whereas the resources provided (such as "*900 +BC*", "*1 SV*", and "*1 BH_SV*") are initialized in the resource pool of the model (see upper right-hand side of Figure 4.5). On the other hand, at the end of sieving one bucket load of *BC*, "*1 SV*" and "*1 BH_SV*" are released, whereas 4 units of *SBC* and 1 unit of *LBC* are produced. Those equipment resources released together with those material resources generated are placed into the resource pool, ready to be reallocated or consumed as simulation proceeds.

Note two trucks ("*TRK_SP*") are deployed to facilitate the "*Trucking SBC*" and "*Trucking LBC*" work flows in the base case scenario. "*1 TRK_SP*" is engaged at the "*Sieve*" location to execute Activity 2 "*Load Small BC*", whereas it is only released at the end of Activity 4 "*Unload to Small BC Stockpile*" at the "*SBCSP*" location. Thus, information on truck returning times from the stockpile location to the "*Sieve*" location is specified in the "*Resource Transit Information System*" attached to the *SDESA* model, which will be queried for updating the state of a returning truck during simulation. In addition, priority settings on flow entities and activities in *SDESA* allow the definition of particular sequences for allocating a resource between parallel work flows. To mirror the actual situation in the present case, the model is configured in such a way that four truck loads of *SBC* would be handled before processing one truck load of *LBC*.

By contrasting the *CYCLONE* model with the *SDESA* model, main differences of the two simulation methods are noted as follows:

- *CYCLONE* uses a grouping of "Combi", "Que", and "Normal" nodes to trace resource flows and map demolition processes; function nodes (generation/consolidation) and directional arrows serve as bridges to logically link up various processes in the site system.
- *SDESA* modeling relies on the identification of work flows and its composite activities and quantity take-off of jobs (flow entities) to be processed by each work flow. The *SDESA* modeling is focused on defining resource requirements at each "Activity" and specifying resources available at the resource pool. Logical relationships between activities and work flows are automatically enforced through allocation, generation, and consolidation of resources, being disposable or non-disposable.

- Information on main site locations and site layout is implicit in the *CYCLONE* model, whereas *SDESA* modeling entails direct mapping of site locations onto activity definition and resource transit information specification.

4.4.3 Extended *SDESA* Model

In terms of modeling a large selective-demolition system, the waste-handling process mapping and *SDESA* simulation provides a more streamlined, better structured, and more convenient approach in comparison with ACD process mapping and the *CYCLONE* modeling. To conduct further study, the *SDESA* model was extended to include 1) collecting and sorting of raw demolition waste; 2) sieving and stockpiling of broken concrete; 3) steel bar recycling; and 4) debris disposal at the landfill. The *SDESA* computer platform was utilized in the present case study, which was developed in-house with user-friendly features for 1) simulation definition; 2) statistical analysis of simulation outputs; and 3) iconic animation over the site layout view.

According to the first-hand information obtained from the site, the following assumptions were made in establishing the simulation model:

1. Weather and temperature are consistently fine and suitable for work.

2. The number of working hours per day is eight, plus a one-hour lunch break (12:00-13:00.)

3. The constituents of the waste material can be segregated by waste sorting and handling mechanisms being applied. For instance, the extraction of *Steel (STL)*, *Broken Concrete (BC)* and nonusable *Debris (DB)* from *Raw Demolition Units (RDU)* by sorting; the segregation of *Broken Concrete (BC)* into *Large Broken Concrete (LBC) and Small Broken Concrete (SBC)* by sieving.

4. The volume of the waste material reduces after compaction. For example, after each truck load ($4.5m^3$) of the *Stockpiled Small Broken Concrete* or the *Stockpiled Large Broken Concrete* is compacted by the bulldozer, $4.0m^3$ (instead of $4.5m^3$) of *Graded Small Broken Concrete* or *Graded Large Broken Concrete* would be produced.

The full *SDESA* simulation model represents an aggregate of multiple work flows. Activities comprising each work flow along with activity times in the form of uniform distributions or constants are summarized in Table 4.1. Note, activities "*Move To Landfill*" and "*Return To Site*" represent trucks moving back and forth between the landfill and the site, subject to traffic jams. To incorporate the effect of traffic jams in the *SDESA* model, a 0.1 probability of occurrence was imposed and the delay time was sampled from a uniform distribution ranging from 10 to 20 minutes. That means on the two transit activities, one out of ten trucks would experience 10 to 20 min added travel time due to traffic jams.

Table 4.1. Activity Definitions of Kai Tak Airport Demolition Project

Work flows	**Activities**	**Duration Input Model (min)**		
		Type	**L**	**U**
Trucking Raw Waste	Load Demolition Unit	Uniform	7	9
	Move To Sort	Uniform	0.4	1
	Unload to Sort	Uniform	0.4	0.7
	Return to Demolition	Uniform	0.3	0.7
Sorting Raw Waste	Sort Raw Waste	Uniform	3	3.5
Stockpiling Steel	Load Steel	Uniform	0.8	1.2
	Move To Steel Stockpile	Uniform	0.5	0.8
	Unload To Steel Stockpile	Uniform	0.3	0.5
	Return to Load Steel	Uniform	0.3	0.6
Stockpiling Debris	Load Debris	Uniform	0.8	1.2
	Move To Debris Stockpile	Uniform	0.6	1
	Unload To Debris Stockpile	Uniform	0.3	0.5
	Return to Load Debris	Uniform	0.4	0.7
Trucking BC To Sieve	Load Broken Concrete	Uniform	0.2	0.25
	Move To Sieve	Constant	0.08	
	Unload To Sieve	Constant	0.1	
	Return to Load Broken Concrete	Constant	0.05	
Sieving BC	Sieve BC	Uniform	0.3	0.5
Stockpiling Small BC	Load Small BC	Uniform	4	5.5
	Move To Small BC Stockpile	Uniform	0.5	0.7
	Unload To Small BC Stockpile	Uniform	0.3	0.5
	Return to Load Small BC	Uniform	0.3	0.5
Stockpiling Large BC	Load Large BC	Uniform	4	6
	Move To Large BC Stockpile	Uniform	0.4	0.6
	Unload To Large BC Stockpile	Uniform	0.3	0.5
	Return to Load Small BC	Uniform	0.2	0.3
Grading Small BC	Compact Small BC	Uniform	3	4.5
Grading Large BC	Compact Large BC	Uniform	4	5
Disposing Debris	Load Stockpiled Debris	Uniform	5	8
	Leave Site - D	Uniform	2	3
	Move To Landfill	Uniform	25	30
	Unload to Landfill	Uniform	5	15
	Return To Site	Uniform	20	25
	Return to Load Debris	Uniform	1	2
Recycling Steel	Move To Load Stockpiled Steel	Uniform	1.5	3
	Load Stockpiled Steel	Uniform	5	10
	Leave Site - S	Uniform	2	4

Note: L = lower limit; U = upper limit.

As detailed site operations data were not kept by the contractor or the consultant, simulation input models (uniform distributions for activity times) were based on limited information available (observations by research personnel and estimates by site personnel.) Note that they realistically represent activity-time ranges but may simplify or underestimate the variability in the actual activity time. Nonetheless, the limitation in input modeling does not pose a serious problem on the follow-up simulation-enabled cost benefit analysis, which is based on averaged project time and resource utilization rates from multiple Monte Carlo duplications.

Table 4.2 lists the key locations of the site layout which were specified in the simulation model for defining 1) the location attributes of activities and 2) the resources' transit distance or time specified in the "*Resource Transit Information System*" (*RTIS*) of the simulation model. Figure 4.6 shows the site layout of the Kai Tak site.

Table 4.2. Key locations of Kai Tak Airport Demolition Project

Location	**X**	**Y**
Demolition	165	335
Sorting	225	315
Sieving	225	270
Steel Stockpile	275	295
Debris Stockpile	320	315
Small BC Stockpile	340	95
Large BC Stockpile	320	55
Site Entrance / Exit	555	350

Note: XY relative coordinates taken from site layout plan

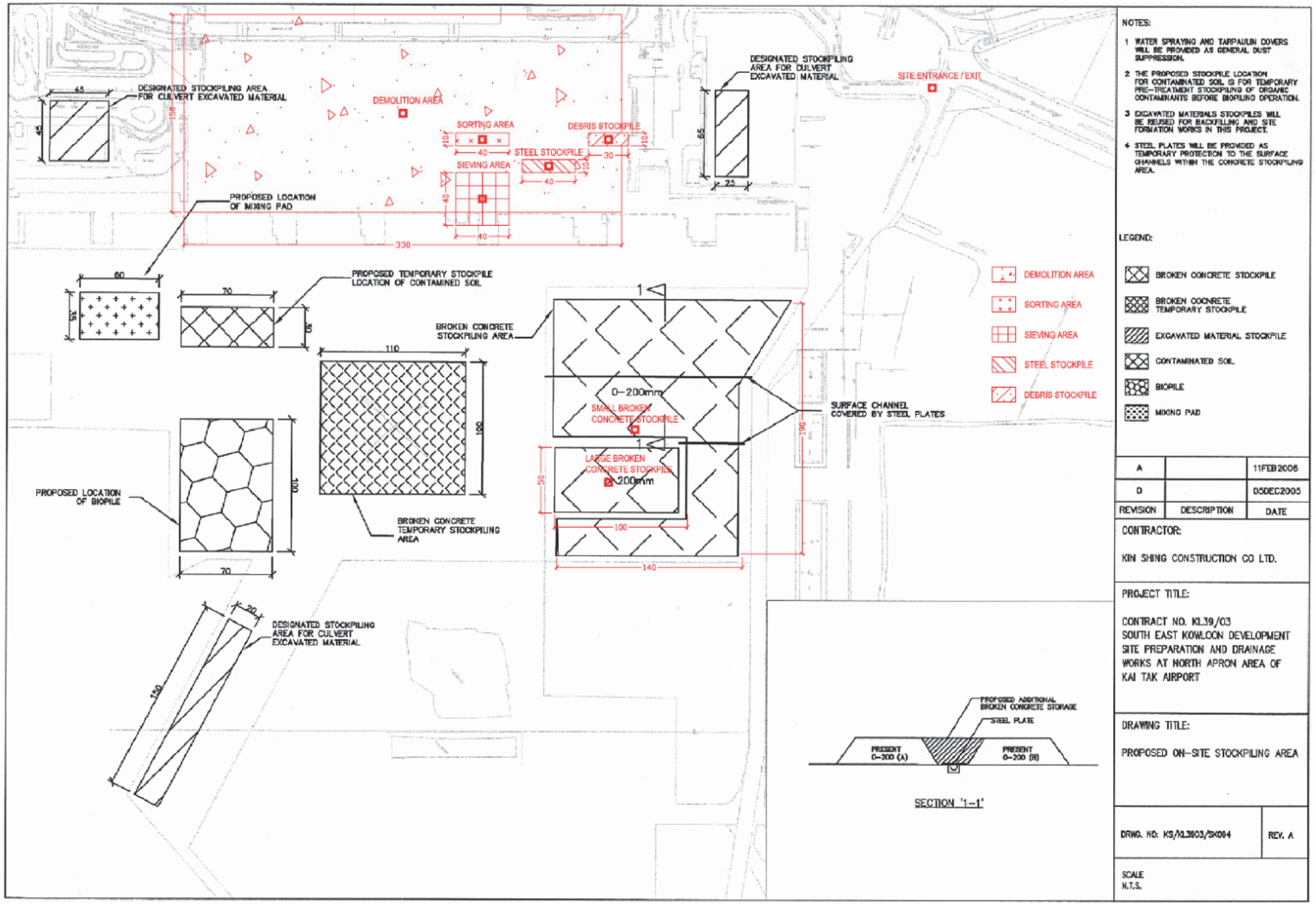


Figure 4.6. Site Layout of Kai Tak Airport Demolition Project

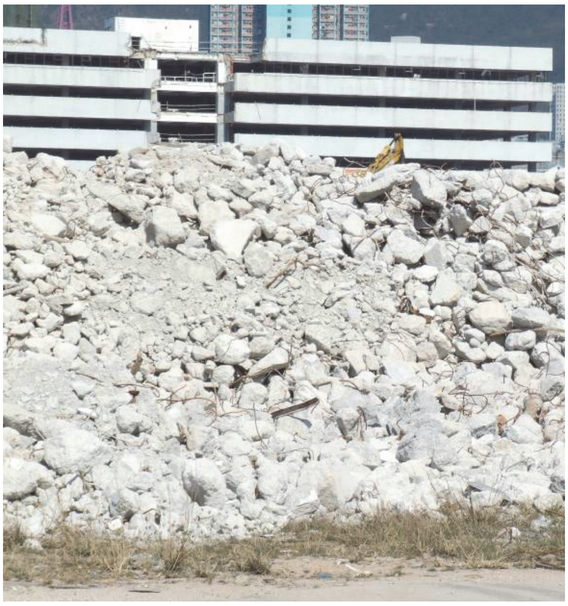
Figure 4.7. Bird's Eye View of Kai Tak Airport Demolition Project

Figure 4.7 shows the bird's eye view of the Kai Tak Site. The detailed non-structural demolition sequence, structural demolition sequences, typical plants involved in demolition works, waste management, and waste generation and handling procedures are described in Appendix F. The demolished materials during on-site sorting were all structural elements as all non-structural demolition was carried out prior to structural demolition by using selective demolition as specified in the contract. A general waste handling process for on-site sorting can be depicted as below. The locations of the working area are indicated in Figure 4.8.

Figure 4.8. Structural Demolition at Demolition Area

At the beginning of the whole process, the *Raw Demolition Unit (RDU)* was stockpiled (see Figure 4.9) at the location where the structural elements were originally demolished from top to down as shown in Figure 4.8. The *Raw Demolition Unit (RDU)* was then collected by three specific backhoes (*BH_RDU*) to three specific trucks (*TRK_RDU*) assigned for transporting *RDU* to the sorting area.

(a)



(b)

Figure 4.9. Raw Demolition Unit (RDU) Stockpiles at Demolition Area

As shown in Figure 4.10. the sorting process would extract the *Debris (DB)* and *reinforcement bars (steel, STL)* from the *RDU*, *Broken Concrete (BC)* was the leftover for the succeeding waste handling activities. It would be transported to the sieving area by a specific backhoe (*BH_MTS*). The debris and steel would then be transported and stockpiled properly to the debris stockpiling area and steel stockpiling area respectively as given in Figure 4.11 and Figure 4.12. The debris would then be disposed of at the landfill by the contractor, whereas the steel would be sold and collected by a recycler.

Figure 4.10. A Backhoe for sorting (*BH_ST*) with a Breaker (*BRK*)

Figure 4.11. Steel Stockpile

Figure 4.12. Debris Stockpile

As shown in Figure 4.13, the broken concrete at the sieving area would then be transferred by a backhoe (*BH_SV*) to a screening plant where it would be sieved to

Small Broken Concrete (SBC) of nominal sizes ranging from 0-200 mm (for those *Sorted Broken Concrete (S_BC)* passing through the screen) and *Large Broken Concrete (LBC)* of nominal sizes ranging from 200-400 mm (for the *Sorted Broken Concrete (S_BC)* rolling along the screen down to the ground).

Figure 4.13 Sieving Area

The *Small Broken Concrete (SBC)* and *Large Broken Concrete (LBC)* were then loaded to trucks (*TRK_SP*) by a backhoe (*BH_SP*) and transported to the Small Broken Concrete Stockpiling Area and the Large Broken Concrete Stockpiling Area accordingly. The *Stockpiled Small Broken Concrete (SP_SBC)* and the *Stockpiled Large Broken Concrete (SP_LBC)* were finally compacted by a *Bulldozer (BDZ)*. Figure 4.14 shows the small and large broken concrete stockpile. For safety reason, the stockpile height was restricted to five metres.

Figure 4.14. Small and Large Broken Concrete Stockpile

Identification of Work Flows

The work flows are identified and their corresponding work units in *SDESA* are listed in Table 4.3.

Table 4.3. Work Flows and Their Corresponding Work Units in Kai Tak Airport Demolition Project

Work Flow	**Work Unit in *SDESA***	**Basic Model Structure (Vehicle Loop (V) / Production Line (P))**	**No. of Work Units (1000 RDU)**	**Disposal Resources Required**	**Capacity per Work Unit**	**Disposal Resources Generated**
Transport RDU to Sorting Area	TRK_RDU	V	3	1000 *RDU*	40 *RDU*	1000 *DU*
Sort DU into BC, STL and DB	Sorting	P	50	1000 *DU*	20 *DU*	900 *BC* 50 *DB* 50 *STL*
Steel Stockpile	Steel Stockpile	V	3	50 *STL*	1 *STL*	50 *SP_STL*
Steel Recycling	R_TRK	V	1	25 *SP_STL*	25 *SP_STL*	-
Debris Stockpile	Debris Stockpile	V	3	50 *DB*	1 *DB*	50 *SP_DB*
Debris Disposal	TRK_DB	V	1	50 *SP_DB*	50 *SP_DB*	50 *D_DB*
Transfer BC to Sieving Area	BH_TTS	V	1	900 *BC*	5 *BC*	900 *S_BC*
Sieve BC into SBC/ LBC	Sieve	P	180	900 *S_BC*	5 *S_BC*	720 *SBC* 180 *LBC*
Small BC Stockpile	Small BC Stockpile	V	3	720 *SBC*	45 *SBC*	720 *SP_SBC*
Large BC Stockpile	Large BC Stockpile	V	3	180 *LBC*	45 *LBC*	180 *SP_LBC*
Grade Small BC	Grade Small BC	P	16	720 *SP_SBC*	45 *SP_SBC*	640 *G_SBC*
Grade Large BC	Grade Large BC	P	4	180 SP_LBC	45 *SP_LBC*	160 *G_LBC*

Location Boundaries of Work Flows

Table 4.4 shows the location boundaries of work flows.

Table 4.4. Location Boundaries of Work Flows in Kai Tak Airport Demolition Project

Work Flow	Work Unit in *SDESA*	Location Boundaries	
		Location 1	**Location 2**
Transport *RDU* to Sorting Area	TRK_RDU	Demolition	Sorting
Sort *DU* into *BC*, *STL* and *DB*	Sorting	Sorting	-
Steel Stockpile	Steel Stockpile	Sorting	Steel Stockpile
Steel Recycling	R_TRK	Site Entrance/ Exit	Steel Stockpile
Debris Stockpile	Debris Stockpile	Sorting	Debris Stockpile
Debris Disposal	TRK_DB	Debris Stockpile	Landfill
Transfer *BC* to Sieving Area	BH_TTS	Sorting	Sieving
Sieve *BC* into *SBC*/ *LBC*	Sieve	Sieving	-
Small *BC* Stockpile	Small BC Stockpile	Sieving	Small BC Stockpile
Large *BC* Stockpile	Large BC Stockpile	Sieving	Large BC Stockpile
Grade Small *BC*	Grade Small BC	Small BC Stockpile	-
Grade Large *BC*	Grade Large BC	Large BC Stockpile	-

Resources Required to Execute Activities

The resources required to drive the activities are classified into three types: Moving Resource (MR), Facilitating Resource (FR) and Disposable Resource (DR). *MR*s refer to flow entities. *FR*s are manpower and machinery resources. *DR*s represent material units, which are generated as intermediate products by one activity, demanded and consumed by another. The resource pool for this case is listed in Table 4.5.

Table 4.5. Resource Pool for Kai Tak Airport Demolition Project

Resource Class	Resource Type	Code	Amount
Moving Resources *(MR)*	Backhoe_Transfer to Sieve	BH_TTS	1
	Recycler's Truck	R_TRK	1
	Truck_Debris	TRK_DB	1
	Truck_Raw Demolition Unit	TRK_RDU	3
	Truck_Stockpilng	TRK_SP	2
	Wheelbarrow	WB	4
Facilitating Resources *(FR)*	Bulldozer	BDZ	1
	Backhoe_General	BH_G	1
	Backhoe_Raw Demolition Unit	BH_RDU	1
	Backhoe_Stockpiling	BH_SP	1
	Backhoe_Sorting	BH_ST	2
	Backhoe_Sieving	BH_SV	1
	Breaker	BRK	2
	Cleaning Labour	CL	4
	Flagman	FM	1
Disposable Resources *(DR)*	Demolition Unit	DU	0
	Steel	STL	0
	Stockpiled Steel	SP_STL	0
	Debris	DB	0
	Stockpiled Debris	SP_DB	0
	Disposed Debris	D_DB	0
	Broken Concrete	BC	0
	Sorted Broken Concrete	S_BC	0
	Small Broken Concrete	SBC	0
	Large Broken Concrete	LBC	0
	Stockpiled Small Broken Concrete	SP_SBC	0
	Stockpiled Large Broken Concrete	SP_LBC	0
	Graded Small Broken Concrete	G_SBC	0
	Graded Large Broken Concrete	G_LBC	0

Process Mapping

The C&D waste handling process was divided into eight major components:

1. Collection of Raw Demolition Units
2. Sorting of Raw Demolition Units
3. Transportation of Steel, Debris
4. Steel Recycling
5. Debris Disposal
6. Transportation of Broken Concrete
7. Sieving Broken Concrete
8. Stockpiling Broken Concrete
9. Compaction of Stockpiled Broken Concrete

1. Collection of Raw Demolition Unit

At the beginning of the whole process (at time=0), the control variable *Raw Demolition Unit (R_DU)* was defined to control the total amount of *RDU* to be handled, whose initial value is set in *SDESA*. *RDU*s were loaded by three specific backhoes (*BH_RDU*) to three specific trucks (*TRK_RDU*) whose volume capacity were 40 units each and transported to the sorting area.

As shown in Figure 4.15, two location circles, "*Demolition Area*" and "*Sorting Area*", were defined in the work flow of *Truck for Raw Demolition Unit* (*TRK_RDU*), with two production activities (i.e. "*Load Demolition Unit*" and "*Unload To Sort*") and two transit activities (i.e. "*Move To Sort*" and "*Return To Demolition*"). A condition for the activity "*Load Demolition Unit*" was set as "*R_DU>0* " (i.e. The amount of R_DU at demolition area was larger than zero). Once activity "*Load Demolition Unit*" is finished (i.e. 40 R_DU was loaded to truck), the control variable is modified as "*R_DU = R_DU - 40*" (i.e. the total amount of R_DU was deducted by 40 units). For each cycle, 40 units of *Demolition Units (40 DU)* were generated at the end of the activity "*Unload To Sort*" as an intermediate material unit to the sorting process. Figure 4.16 shows the *SDESA* model of the work flow.

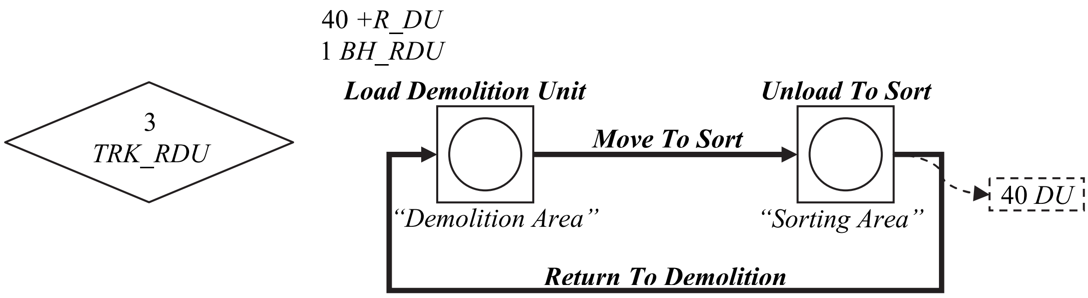


Figure 4.15. Process Mapping Model of Collection of Raw Demolition Unit Work Flow

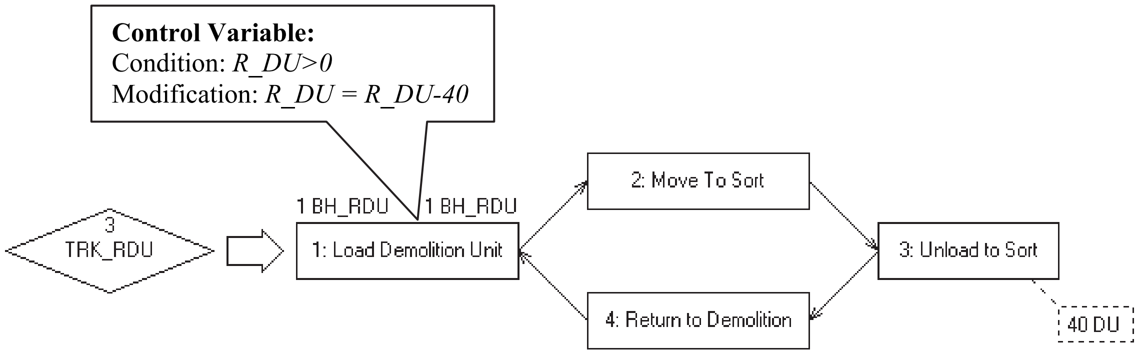


Figure 4.16. *SDESA* Model of Collection of Raw Demolition Unit Work Flow

2. Sorting

Upon the unloading from the *TRK_RDU* at the "*Sorting Area*" (*location circle*), 40 units of *Demolition Units* (40 *+DU*) (the "+" prefix of *DU* indicates disposability of a resource) were available for sorting. During the sorting process, for each 20 unit of *Demolition Units* (20 *DU*) broken by a backhoe (1 *BH_ST*) together with a *breaker* (1 *BRK*), 1 unit of *Debris* (1 *DB*), 1 unit of *reinforcement bars* (*steel,* 1 *STL*), and 18 units of *Broken Concrete* (18 *BC*) were generated as the intermediate products for the succeeding waste handling activities. The products generated were estimated by the volumetric proportion of various components that make up the *DU*. Fifty work flows would be processed for each 1000 *RDU* as calculated in quantitative measurements. Figure 4.17 and Figure 4.18 shows the mapping model and *SDESA* model respectively.

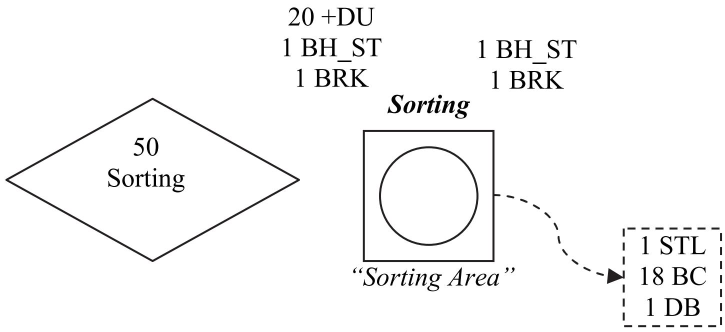


Figure 4.17. Mapping Model of Sorting Work Flow

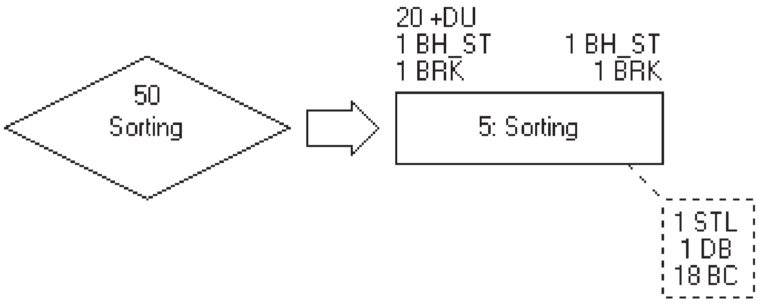


Figure 4.18. *SDESA* Model of Sorting Work Flow

3. Transportation of Steel and Debris

After sorting the *Demolition Units*, the *Steel* (*STL*) and *Debris* (*DB*) would be transported and stockpiled from "*Sorting Area*" to the "*Steel Stockpiling Area*" and "*Debris Stockpiling Area*" respectively. The two waste handling processes required the same resources, a *Wheelbarrow* (*WB*) as the *moving resource* (*MR*) and a *Cleaning Labour* (*CL*) as the *facilitating resource* (*FR*).

Conversion of *VL* Type Work Flows into *PL* Type Work Flows

After sorting the *Demolition Units*, the *Steel "STL"* and the *Debris "DB"* would be transported and stockpiled from *Sorting Area* to the *Steel Stockpiling Area* and the

Debris Stockpiling Area respectively. The two material handling processes required the same resources, a *Wheelbarrow "WB"* as the *moving resource (MR)* and a *Cleaning Labour "CL"* as the *facilitating resource (FR)*.

Note that the traditional use of two individual *VL* type work flows by assigning two *WB's* to each work flow cannot mirror the flexibility of resource sharing in practical situations (four *WB's* were shared between the deliveries of *STL* and *DB*). Instead, two *PL* type work flows are adopted to achieve such purpose. *Steel Stockpile* requires the availability of the combination of one *WB* (*MR*) with one *Steel "1 STL" (DR),* whereas *Debris Stockpile* requires the availability of the combination of *"1 WB" (MR)* with one *Debris "1 DB" (DR)*. The number of *MR's* are defined the resource pool for the work flows representing the maximum number of concurrent work tasks.

By using two *PL* type work flows: *"Steel Stockpile"* (Figure 4.19) and *"Debris Stockpile"* (Figure 4.20), the four *WB's* can now be shared between the delivery cycles by combining with respective *DR's*. As there are four *WB's* available, the numbers of resources are equal to the maximum number of concurrent work tasks which is four. The work flows will be executed once there is any free *WB* and its driver *CL*, together with the presence of *STL* or *DB* units; upon delivery the materials to their corresponding destinations, one unit of *Stockpiled Steel "1 SP_STL"* or one unit of *Stockpiled Debris*

"1 SP_DB" will be produced for *Steel Recycling* and *Debris Disposal* work flows respectively.

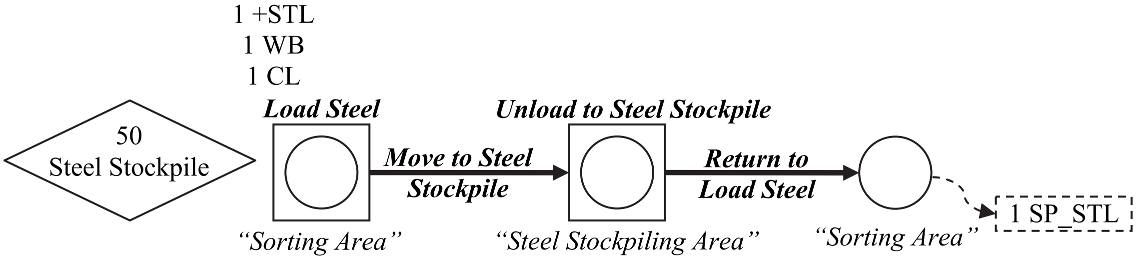


Figure 4.19. Process Mapping Model of *Steel Stockpile* Work Flow

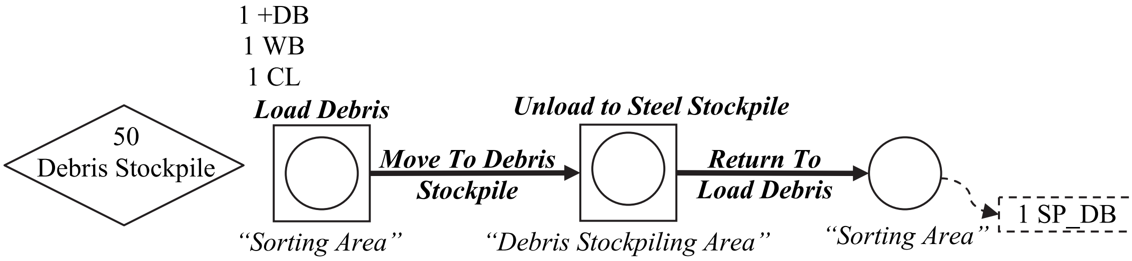


Figure 4.20. Process Mapping Model of *Debris Stockpile* Work Flow

4. Steel Recycling

Upon the *Stockpiled Steel* (*SP_STL*) accumulated reaching 25 units, the contractor would notice the steel recyclers to collect the *SP_STL*. The Recycler would then send a truck (*R_TRK*) to collect the *SP_STL*, a *flagman* (1 *FM*) would lead the truck to the "*Steel Stockpiling Area*" where the *SP_STL* was loaded by a backhoe (1 *BH_G*). The truck would leave the site and await the signal for another cycle. The mapping model and *SDESA* model of the steel recycling work flow is given in Figure 4.21 and 4.22 correspondingly.

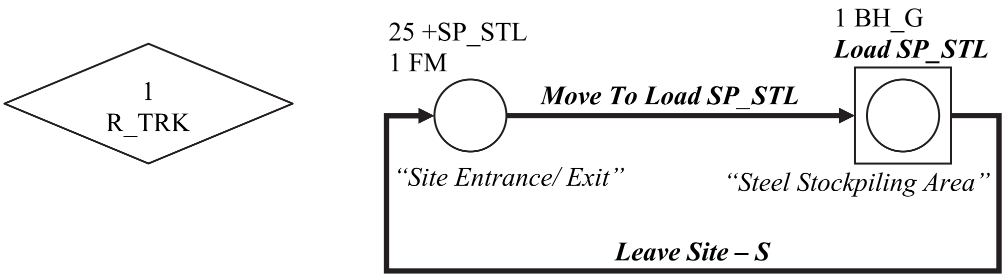


Figure 4.21. Process Mapping Model of Steel Recycling Work Flow

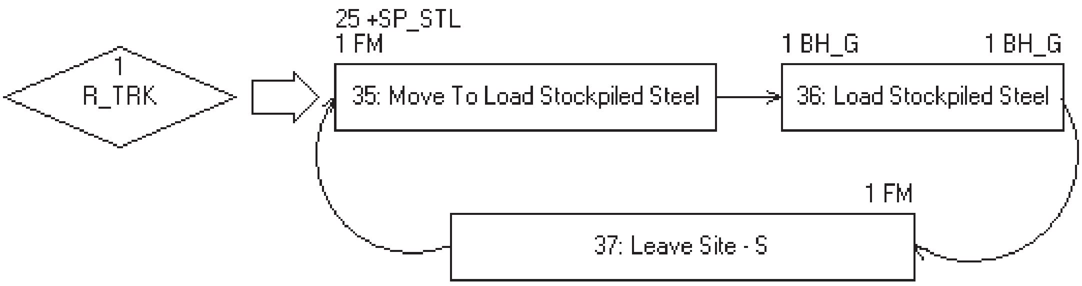


Figure 4.22. *SDESA* Model of Steel Recycling Work Flow

5. Debris Disposal

Figure 4.23 shows the mapping model of debris disposal work flow. Once the *Stockpiled Debris* (*SP_DB*) had built up to 50 units, they would be loaded by a backhoe (1 *BH*) to a truck (1 *TRK_DB*) and transported to South East New Territories Landfill at Tseung Kwan O ("*Landfill*" for short) for disposal. Fifty units of *Disposed Debris* (50 *D_DB*) would be generated and the truck would then return to site. In *SDESA* model as shown in Figure 4.24, the activity "*Move To Landfill*" would be separated into "*Leave Site – D*" and "*Move to Landfill*", whereas another activity "*Return To Debris*

Stockpiling Area" would be separated into "*Return To Site*" and "*Return to Load Debris*" so that the visualization of the animation in site layout would be more easily followed by adding the checkpoint "*Site Entrance / Exit*" for both transitions.

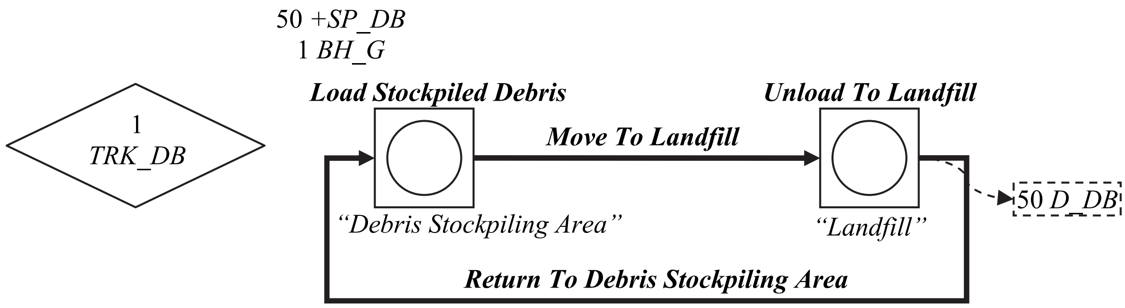


Figure 4.23. Process Mapping Model of Debris Disposal Work Flow

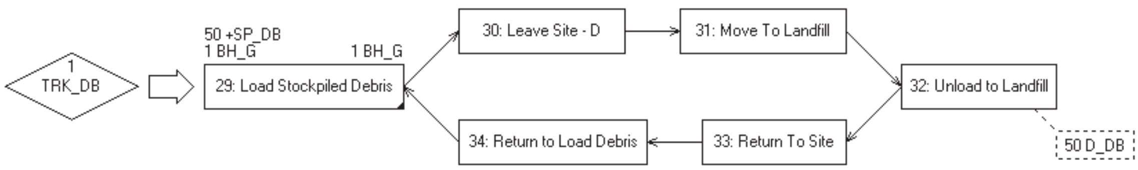


Figure 4.24. *SDESA* Model of Debris Disposal Work Flow

6. Transportation of Broken Concrete

The *Broken Concrete* (*BC*) at the "*Sorting Area*" would be transported to the "*Sieving Area*" by a backhoe (1 *BH_TTS*). Each bucket contained 5 units of *Broken Concrete* (5 *BC*) which would be unloaded as 5 units of *Sorted Broken Concrete* (5 *S_BC*) as intermediate products for "*Sieving*". The mapping model and *SDESA* model is given in Figure 4.25 and Figure 4.26 respectively.

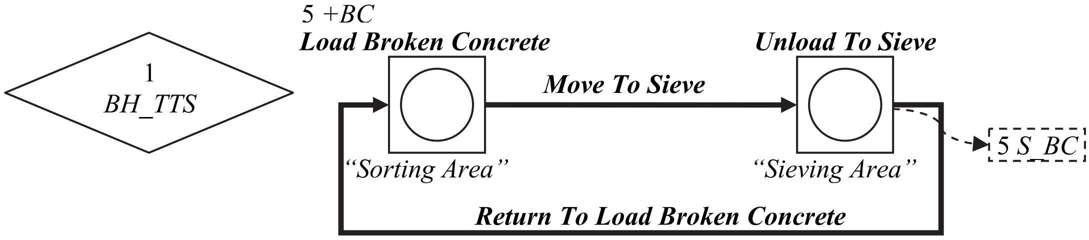


Figure 4.25. Mapping Model of Transportation of Broken Concrete Work Flow

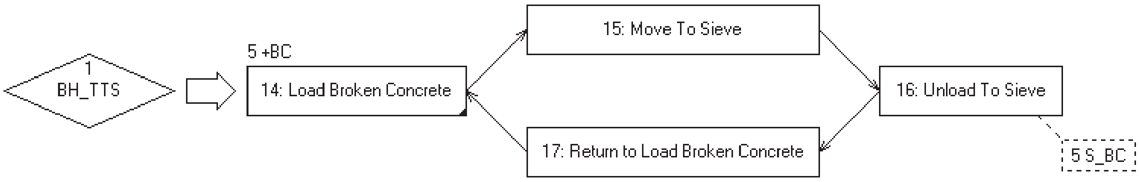


Figure 4.26. *SDESA* Model of Transportation of Broken Concrete Work Flow

7. Sieving Broken Concrete

The *Sorted Broken Concrete* (*S_BC*) at the sieving area would be transferred by a backhoe (1 *BH_SV*) to a screening plant where they would be sieved into 1) *Small Broken Concrete (SBC)* of nominal sizes ranging from 0-200 mm, which passed through the screen; and 2) *Large Broken Concrete (LBC)* of nominal sizes ranging from 200 to 400 mm, which did not pass through the screen and rolled down to the ground at the end of the screen plant. The ratio for *SBC* to *LBC* was 4:1, therefore each bucket of 5 units (5 *S_BC*) would produce 4 units of *SBC* (4 *SBC*) and 1 unit of *LBC* (1 *LBC*). This production line would process for 180 times per 1000 *R_DU* to complete the sieving process as determined in the quantitative measurements. The mapping model and *SDESA* model are presented in Figure 4.27 and Figure 4.28 respectively.

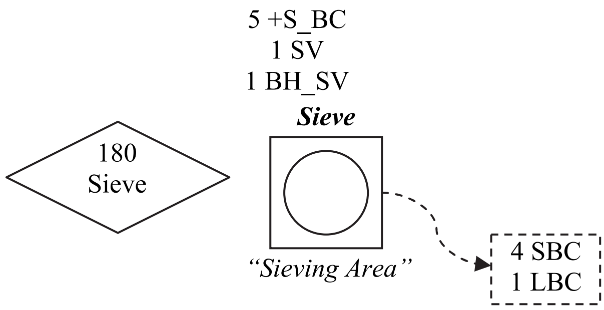


Figure 4.27. Mapping Model of Sieving Work Flow

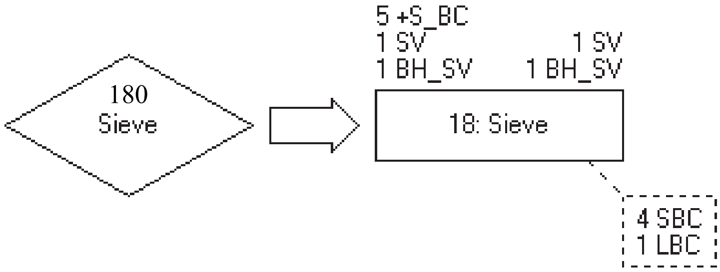


Figure 4.28. *SDESA* Model of Sieving Work Flow

8. Stockpiling Broken Concrete

The *Small Broken Concrete (SBC)* and *Large Broken Concrete (LBC)* were then loaded into trucks (*TRK_SP*) by a backhoe (*BH_SP*) and transported to Small Broken Concrete Stockpiling Area and Large Broken Concrete Stockpiling Area accordingly. The mapping model of broken concrete stockpiling work flow is shown in Figure 4.29.

Similar to the situations of "*Steel Stockpile*" and "*Debris Stockpile*", the *Combination Units* were used in *SDESA* model for the activities "*Small BC Stockpile*" and *"Large BC Stockpile"* to simulate 3 *TRK_SP*s (*MR*s) shared between these activities which were executed by combining 1 *TRK_SP* with either 45 units of *SBC* (45 *SBC*) or 45 units of *LBC* (45 *LBC*) (*DR*s). A backhoe (1 *BH_SP*) served as the facilitating resource for the activity "*Load Small BC*" which loaded the *SBC* or *LBC* to the *TRK_SP*s. Forty-five units of *Stockpiled Small Broken Concrete* (45 *SP_SBC*) or *Stockpiled Large Broken Concrete* (45 *SP_LBC*) were generated as intermediate products for the follow-up compaction operations. The *SDESA* model of the work flow is given in Figure 4.30.

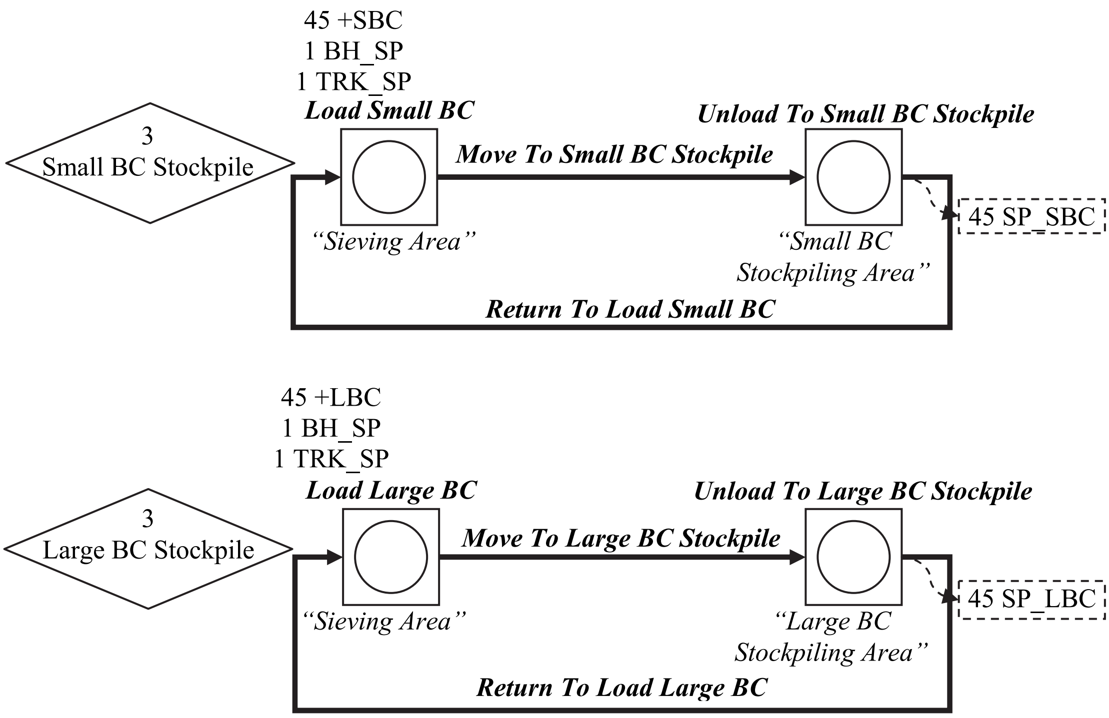


Figure 4.29. Mapping Model of Broken Concrete Stockpiling Work Flow

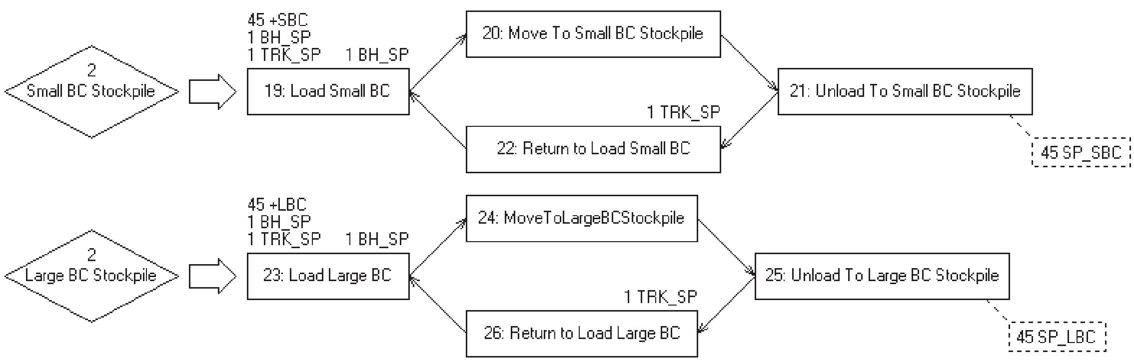


Figure 4.30. *SDESA* Model of Broken Concrete Stockpiling Work Flow

9. Compaction of Stockpiled Broken Concrete

For each truck of *Stockpiled Small Broken Concrete (SP_SBC)* and *Stockpiled Large Broken Concrete (SP_LBC)*, they would be compacted by a *Bulldozer* (*BDZ*) which was mobilized between two stockpiling areas. Note that the volumetric changes occurred during the compaction. For each 45 units of *SP_SBC* (45 *SP_SBC*) or *SP_LBC* (45 *SP_LBC*), they would be compacted into 40 units of *Graded Small Broken Concrete* (40 *G_SBC*) or *Graded Large Broken Concrete* (40 *G_LBC*). This denotes the volume reduction of broken concrete by compaction. Sixteen "*Grade Small BC*" and four "*Grade Large BC*" would be processed per 1000 *R_DU* as determined in the quantitative measurements. The mapping model and *SDESA* model of compaction work flow are given in Figure 4.31 and Figure 4.32 accordingly.

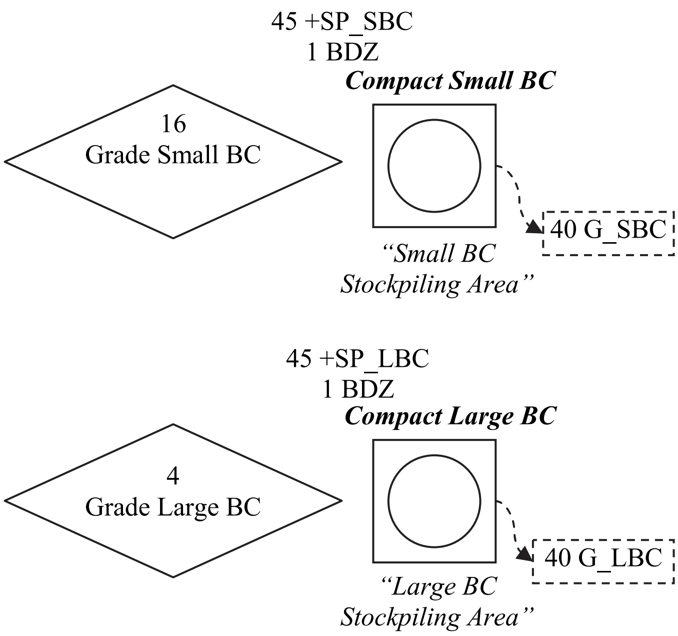


Figure 4.31. Mapping Model of Compaction Work Flow

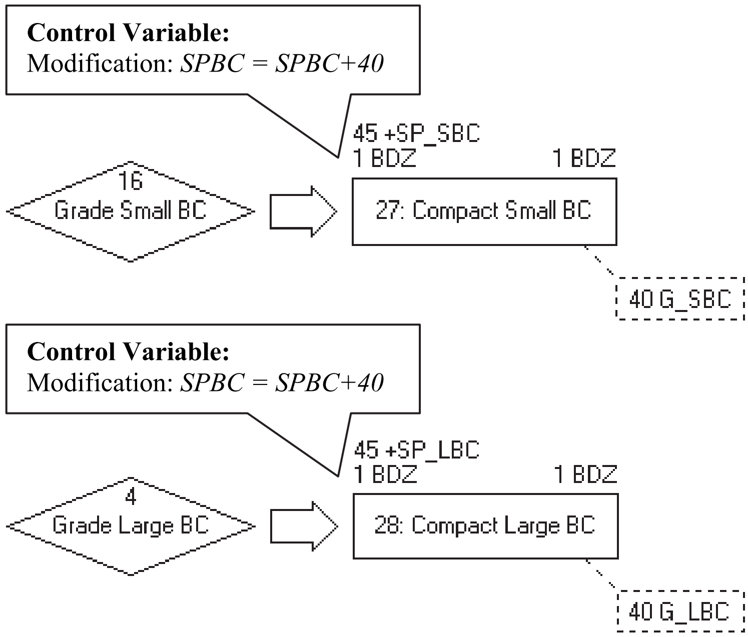


Figure 4.32. *SDESA* Model of Compaction Work Flow

Activity Interruptions

The activities "Move To Landfill" and "Return To Site" were off-site and subjected to traffic jams, the interruption probability of 0.1 would be assumed with the interruption duration of uniform distribution between 10 minutes and 20 minutes for both activities.

Resource Transit Information System

The Bulldozer was shared between the activities "*Grade Large Broken Concrete*" and "*Grade Small Broken Concrete*". The Backhoe_General was served for two activities – "*Load Stockpiled Debris*" and "*Load Stockpiled Steel*". As shown in Figure 4.33, the Resource Transit Information System (*RTIS*) states the transition duration for the resources moving between different locations.

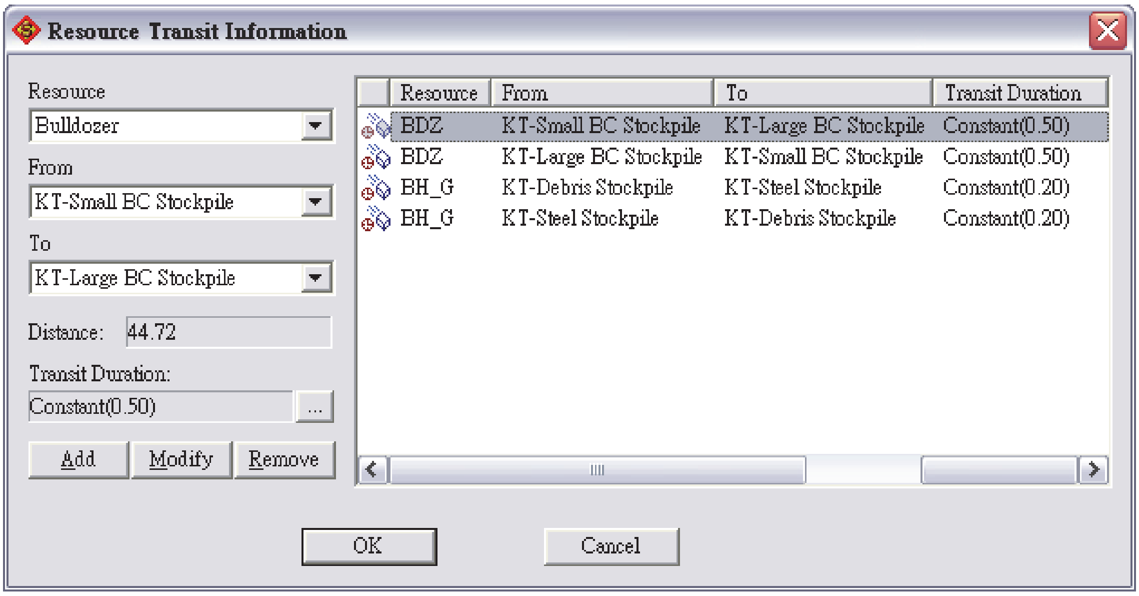


Figure 4.33. Specifying Additional Transit Information of *FR* in *RTIS* of Simulation Model

Figure 4.34 presents the total *SDESA* model with all the above settings given above incorporated. The simulation output can be observed though animation view. Figure 4.35 shows a screenshot of animation view of the total model in *SDESA*. The animation view can also be overlaid on site photo (see Figure 4.36) or site plan (see Figure 4.37).

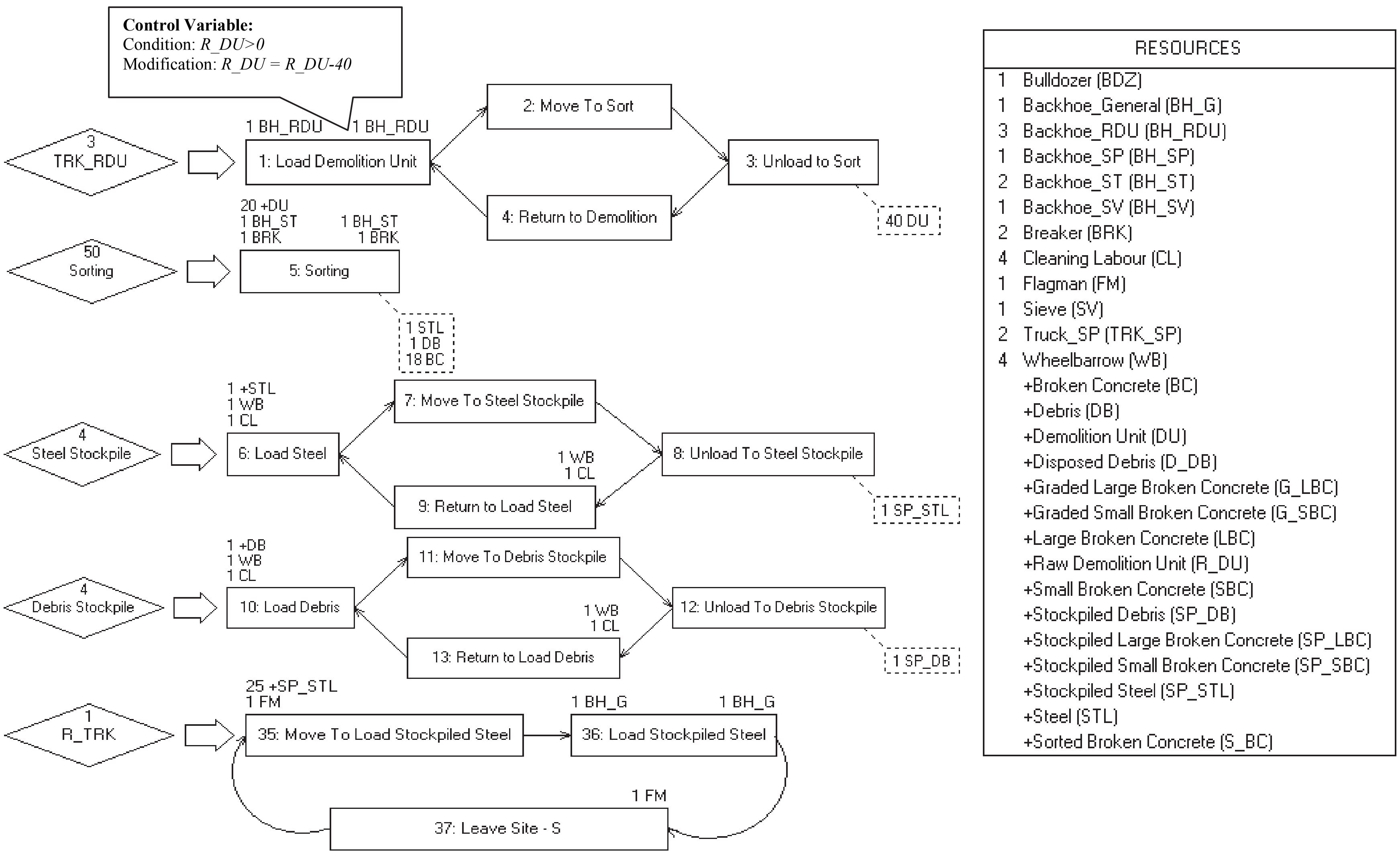


Figure 4.34. Total Model of Kai Tak Airport Demolition Project in *SDESA*

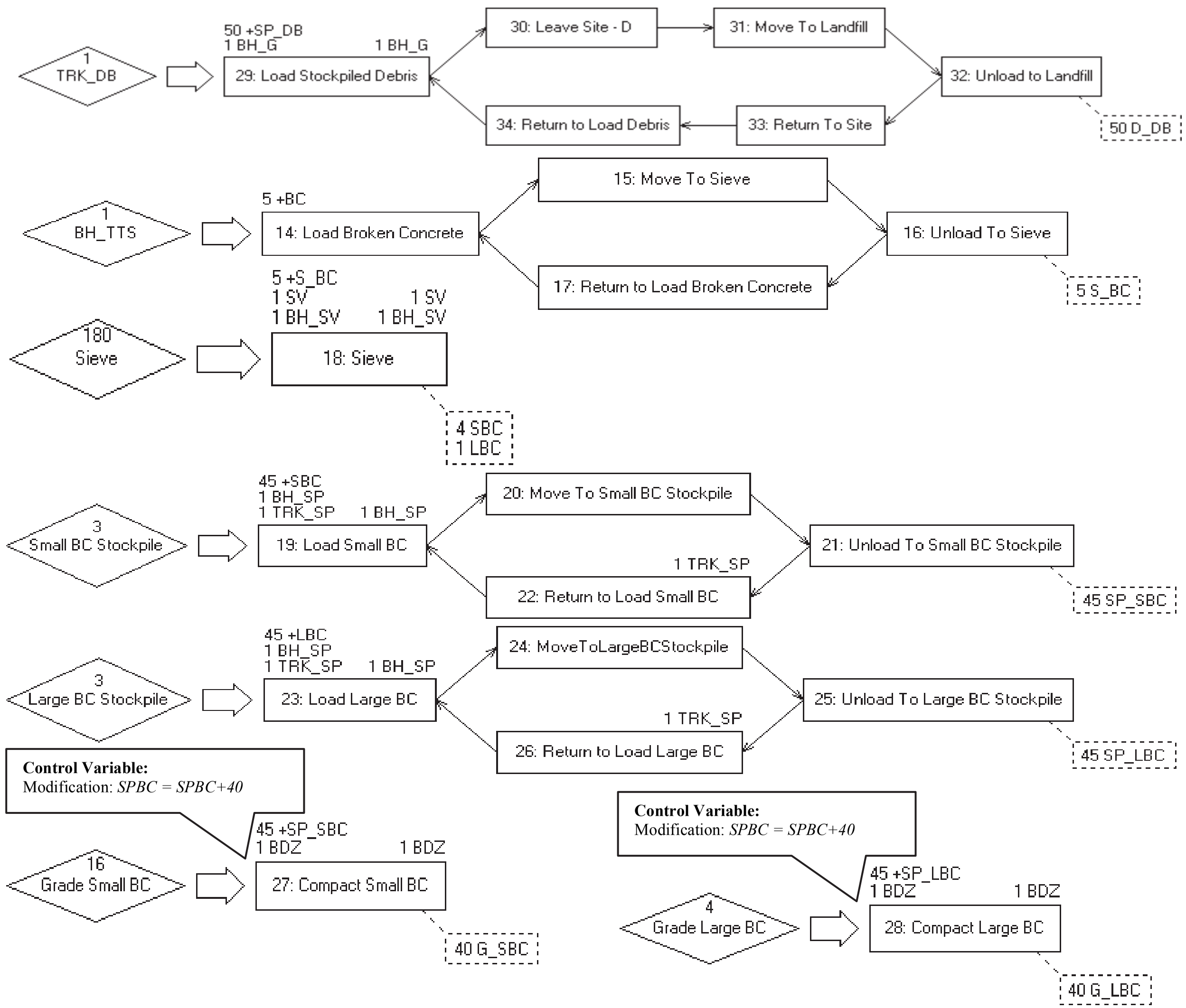


Figure 4.34. Total Model of Kai Tak Airport Demolition Project (con't)

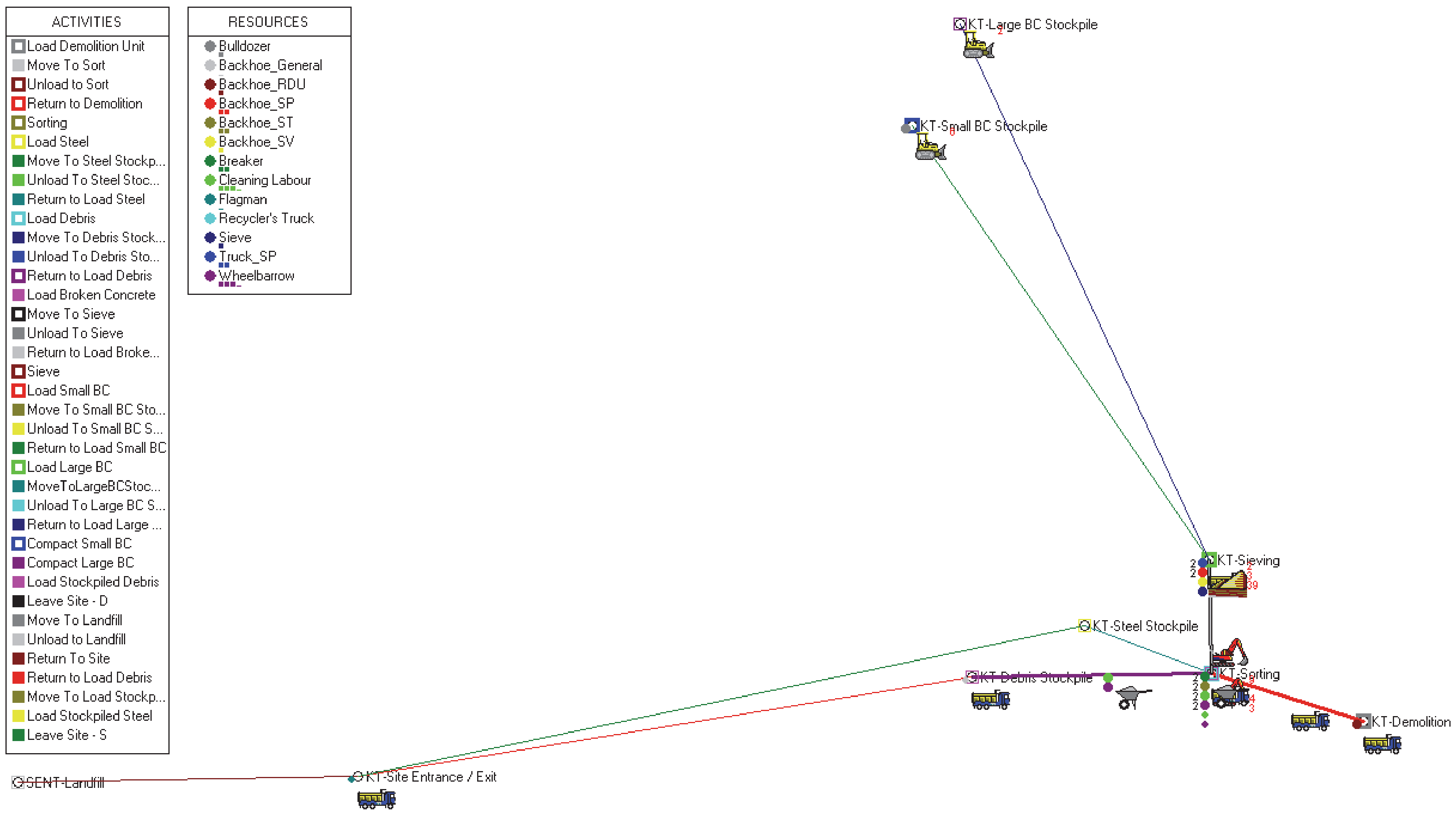


Figure 4.35. Screenshot of Animation View of Kai Tak Airport Demolition Project in *SDESA*

Figure 4.36. Screenshot of Animation View of the Total Model of Kai Tak Airport Demolition Project in *SDESA* Overlaid on Site Photo

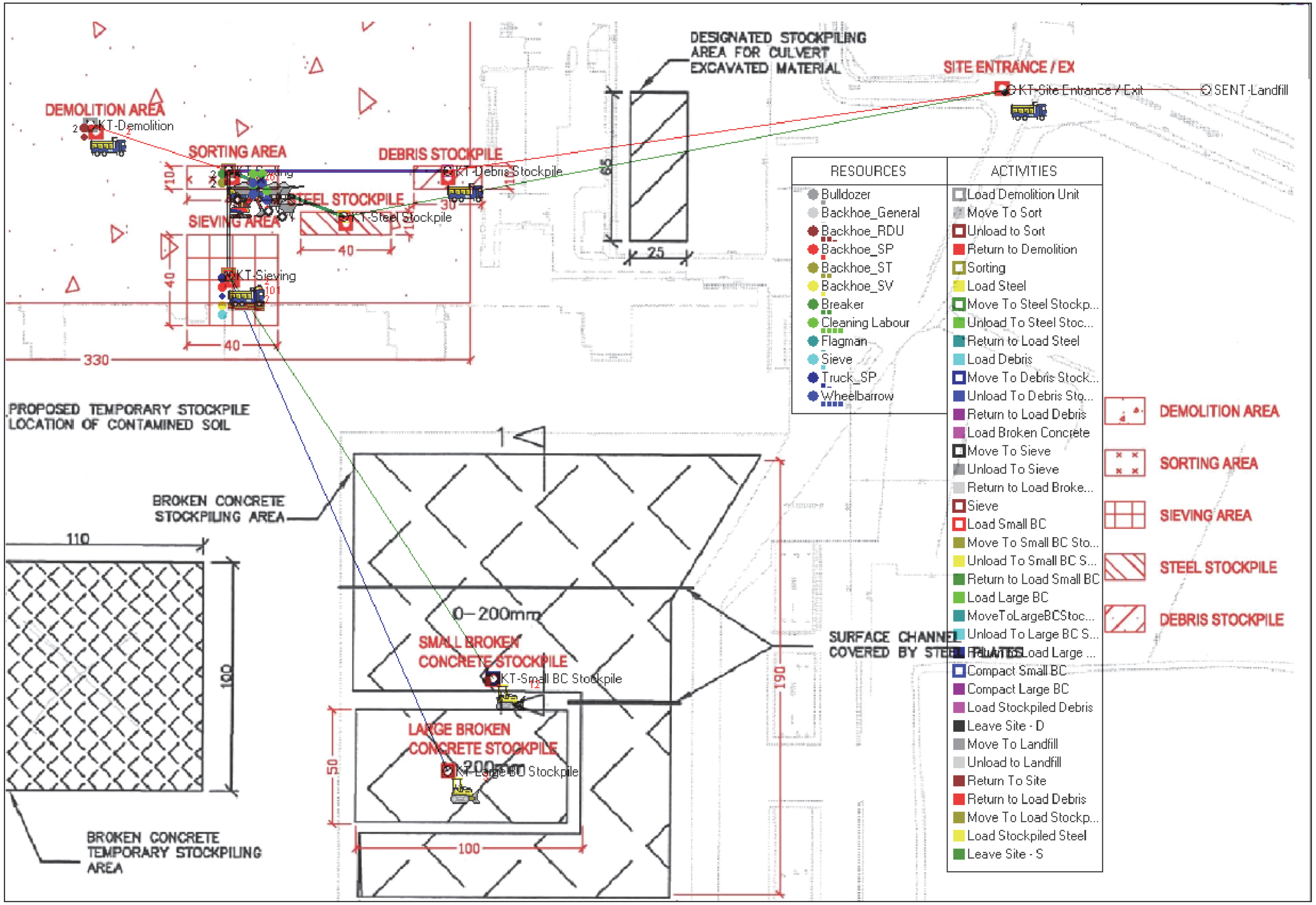


Figure 4.37. Screenshot of Animation View of the Total Model of Kai Tak Airport Demolition Project in *SDESA* Overlaid on Site Map

4.5 Validation of Simulation Model

In order to validate the simulation model, the daily production rate in terms of the quantity of broken concrete being processed was derived from executing a *SDESA* simulation model that closely mirrored site operations and resource provisions as observed in February 2006. Then, the production rate for broken concrete was also obtained from the site record for cross checking the simulation result. Note that site visits were made during February 2006 and the simulation model is supposed to be a close parallel of the actual operation in that month. According to the C&D material report provided by the client, as for February 2006, the total amount of broken concrete produced was 23,653 tons. Given the estimated density of broken concrete of 2.0 ton/m^3 and 26 work days per month, the actual daily production rate for broken concrete was determined as 454.8 m^3 per day. The production rate obtained from the simulation model was averaged 460.8 m^3 per day from one hundred runs of Monte Carlo simulation (the standard deviation was 1.6 m^3 per day). The simulation model was further validated by animation of the demolition processes being simulated in the *SDESA* platform. The animation was able to depict waste handling processes and resource moving patterns that resembled the actual site operation.

4.6 Selection of Optimum Simulation Model Size

The scope of simulation model refers to the geographical and time boundaries of a model where the simulation problem is concerned. For the time boundary, the whole construction project can be modeled for a definite scope of works of limited quantity. However, performances of the commonly available computers that will provide the computing platform to execute the simulation models in the construction applications impose a limitation to the time boundary such that the simulation model needs to be scaled down to a controllable size for the subsequent scenario simulation experiments and model optimization. Alternatively, only part of the construction project or a finite period may be modeled if the project last for a very long time with repetitive activities from period to period without significant changes on site activities or geographical locations.

The Kai Tak demolition project lasted for years with similar selective demolition procedures carried out. It is not practical to run a full model due to the limited computer power. Section 4.6.2 demonstrates the preliminary tests carried out to decide the optimum simulation model size.

4.6.1 Model Size versus Production Rate

Apart from the traditional idea of construction waste recycling, the waste handling process of Kai Tak site can also be viewed in another way - the production of broken concrete. This can be validated from the fact that the consultant supervised the monthly production amounts of stockpiled broken concrete, small and large, which provided the indicator of the overall progress of waste handling process.

The production rates of different model sizes simulating the actual system were analyzed. The production rates were compared with that of the actual system to obtain a satisfactory model which maintains the reliability while requiring relatively short simulation time.

The contract period was thirteen and an half months, subtracting the first half month for site preparation period and the non-structural demolition process, and deducting a month for the double handling involved in practice to facilitate the box culvert construction, twelve months was the total project duration. Therefore the production rate of the actual system can be calculated as below:

$$\text{Actual Production Rate} = \frac{\text{Broken Concrete Produced (unit)}}{\text{Total Duration (min)}}$$

$$= \frac{1154000\,\text{unit}}{12\,\text{month} \times \frac{26\,\text{work day}}{1\,\text{month}} \times \frac{8\,\text{hr}}{1\,\text{work day}} \times \frac{60\,\text{min}}{1\,\text{hr}}}$$

$$= 7.71\ \text{unit/min}$$

4.6.2 Preliminary Tests to Decide Optimum Simulation Model Size

A preliminary test set was done before the model validation to get an optimum model size which is representative enough and its corresponding running time should not be too long. Single runs on *SDESA* models were performed on a personal computer with the configuration listed below:

- Windows XP Version 2002 SP2
- Pentium® 4 CPU 3.00 GHz
- 512MB RAM

Table 4.6 shows the total duration simulated from the models with the quantity of broken concrete production being $\frac{1}{1440}$ x, $\frac{1}{160}$ x, $\frac{1}{40}$ x and $\frac{1}{10}$ x the actual total quantity of broken concrete production in the actual system. The larger is the simulation size, not only the higher the model accuracy, but also the longer the computing time. The selection of model scale should not compromise the simulation time or modeling accuracy.

Table 4.6. Simulated Production Rate and Process Time of Model of Different Scales

	Ratio of Model Scale to Actual Work	**Broken Concrete Produced (unit)**	**Total Duration (min)**	**Process Time (h:m:s)**	**Entity Processed**	**Simulated Production Rate (unit/min)**
Actual	1:1	1154000	162240	-	-	7.11
Simulation	$\frac{1}{10}$x	115200	11704	1:18:53	36000	9.73
Simulation	$\frac{1}{40}$**x**	**28800**	**3017**	**0:04:59**	**9000**	**9.55**
Simulation	$\frac{1}{160}$x	7200	821	0:00:20	2250	8.77
Simulation	$\frac{1}{1440}$x	800	168	0:00:01	250	4.76

Running simulation duplications by 100 runs for each case, (except 30 runs for $\frac{1}{10}$x), the production rate in unit/min was then plotted against the total duration in minutes in Figure 4.38.

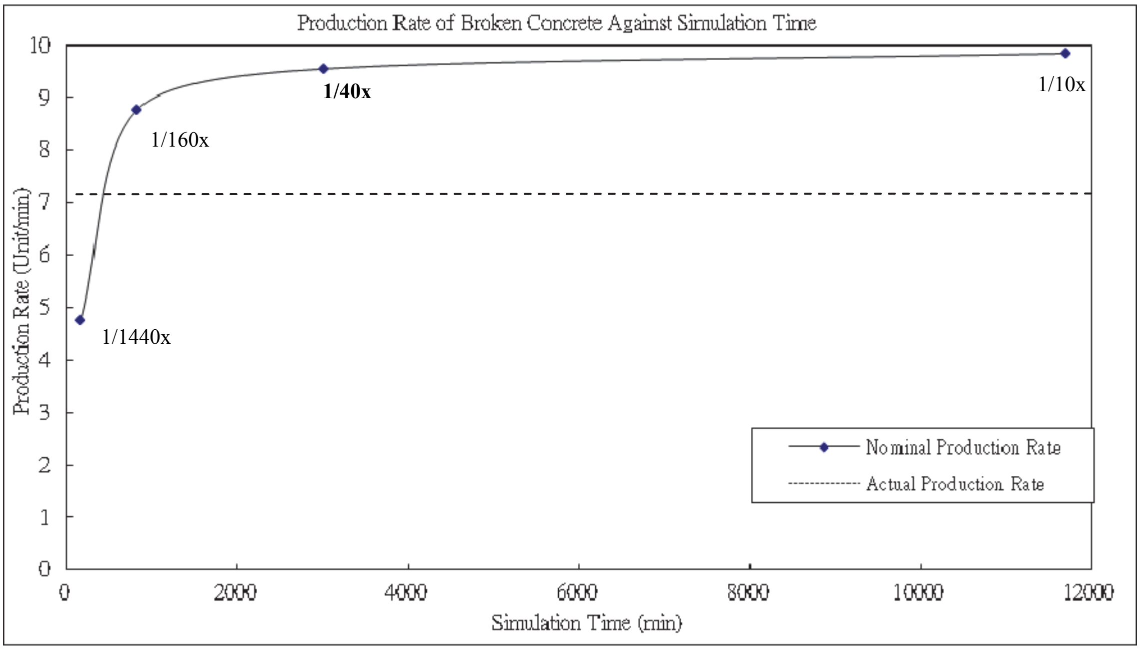


Figure 4.38 Production Rate against the Simulation Time

From the graph, the nominal production rate of the model with the scale $\frac{1}{1440}$x is 4.76 unit/min, did not fulfill the target requirement (7.71 unit/min). On the other hand, the nominal production rates of the models with scale $\frac{1}{160}$x, $\frac{1}{40}$x and $\frac{1}{10}$x are 8.77, 9.55 and 9.73 unit/min respectively and meet the target requirement. Moreover, the production rate increases with a decreasing rate as simulation time increases. The production rate becomes steady at about 9.55 unit/min at the scale $\frac{1}{40}$x. Further enlargement of the model size to $\frac{1}{10}$x will only increase the production rate to 9.73 unit/min which is quite similar to that of $\frac{1}{40}$x. Therefore, the simulation model of scale $\frac{1}{40}$x will be used for the analysis of the different scenarios in the latter part of the study in order to have a good tradeoff between the running time of the simulation program and reliable simulation results.

The explanation and further analysis of the trend of the production rate against the simulation time (scale of the model size to the actual system) will be discussed in the next section.

4.6.3 Analysis of Broken Concrete Production Rates in Different Model Scales

In this section, the production rates of the total broken concrete (production rates for short) in different model scales were compared by monitoring the control variable *SPBC* in the *SDESA* model.

SPBC stands for the Stockpiled Broken Concrete (sum of the Stockpiled Small Broken Concrete and the Stockpiled Large Broken Concrete). This control variable was initially set as 0 and increased by 40 per each activity run of either *"Compact Small BC"* or *"Compact Large BC"*. As these two activities were the ends of the whole production line, the *SPBC* was the end product of the waste handling process.

Figure 4.39, Figure 4.41, Figure 4.43, and Figure 4.45 show the production rates of the models of scales $\frac{1}{1440}$ x, $\frac{1}{160}$ x, $\frac{1}{40}$ x and $\frac{1}{10}$ x respectively. In these figures, the broken concrete produced in units was plotted against time in minutes. Best-fit linear trend lines were then fitted into the curves. The slope refers to the production rate (unit/min) and x-intercept represents the *"Warm Up" Period*.

The production period can be divided into three periods: *"Warm Up" Period*, *"Up Running" Period* and *"Cool Down" Period*.

"Warm Up" Period (sometimes known as run-in period) is a common term originally used in manufacturing and refers to the start time period required in which the whole production line is fully operated and seldom used in construction because the simulation models of construction activities were usually in a short period and seldom involved in a very long time of repetitive works. However, the *"Warm Up" Period* of the production rate becomes significant in this study as the project size is large and this period can explain for the low production rate of small scale model and the increasing trend of the production rate against the simulation model size.

"Up Running" Period refers to the period during which the whole production line is fully operating. It is shown in the constant slope portion of the curve in the figures. The production rate is the actual production rate of the model and can be compatible with the actual system.

"Cool Down" Period is the time when there is no production involved except for the other activity processes in order to complete the whole process. The *"Cool Down" Period* refers to the time when the debris disposal is still in process in the last 50 to 60 minutes of the simulation time after the production of the broken concrete is completed.

Figure 4.40, Figure 4.42, Figure 4.44, and Figure 4.46 show the production rates of the models of the scale $\frac{1}{1440}$ x, $\frac{1}{160}$ x, $\frac{1}{40}$ x and $\frac{1}{10}$ x respectively. In these figures, the broken concrete production rate in unit per minute was plotted against time in minutes. The real-time production rate is determined by dividing the each batch of broken concrete production (40 units) by the time interval corresponding with the production.

$$\text{Real-time production rate} = \frac{\text{Production in } Ti}{T_i}$$

$$= \frac{40\ unit}{T_i\,(\text{min})}$$

where T_i is the i-th period for i=1,2,3…

In addition, three periods are defined as below:

T_1 = *"Up Running" Period*

T_2 (production period) = *"Warm Up" Period* + *"Up Running" Period*

T_3 (whole simulation time) = *"Warm Up" Period* + *"Up Running" Period* + *"Cool Down" Period*

$$P_1 \text{ production rate} = \frac{\text{Total Production in } T_1}{T_1}$$

$$= \frac{\text{Production in "}\textit{Up Running" Period}}{\textit{"Up Running" Period}}$$

$$P_2 \text{ production rate} = \frac{\text{Total Production in } T_2}{T_2}$$

$$= \frac{\text{Production in (}\textit{“Warm Up” Period} + \textit{“Up Running” Period}\text{)}}{\textit{“Warm Up” Period} + \textit{“Up Running” Period}}$$

$$= \frac{\text{Total Production}}{\textit{SPBC}\text{ Production End Time}}$$

P_3 production rate

$$= \frac{\text{Total Production in } T_3}{T_3}$$

$$= \frac{\text{Production in (“}\textit{Warm Up” Period} + \text{“}\textit{Up Running” Period} + \text{“}\textit{Cool Down” Period}\text{)}}{\text{“}\textit{Warm Up” Period} + \text{“}\textit{Up Running” Period} + \text{“}\textit{Cool Down” Period}}$$

$$= \frac{\text{Total Production}}{\text{Simulation End Time}}$$

When simulated production rate is determined as P_3 production rate by simply getting the simulation end time from the model, the result will be underestimated as two factors will increase the idle time of the production. The first one is the *“Warm Up” Period* in which the production starts at the beginning from the Raw Demolition Units (*RDU*) (raw material) to the pass through processes (production line) to produce the *SPBC* (final product). The second one is the *“Cool Down” Period* results from the long debris disposal time at the last 50 to 60 minutes of the simulation time and no production is involved during this period. Therefore, the simulated production rate will be underestimated.

When the simulated production rate is selected as P_2 production rate by getting the end time of the *SPBC* control report from the model, the result will still be underestimated as including the *“Warm Up” Period* will obtain a lower average production rate.

The comparison of using T_1, T_2 and T_3 production time to calculate their corresponding production rate P_1, P_2 and P_3 is demonstrated in the follow section.

4.6.4 Broken Concrete Production Rate with scale $\frac{1}{1440}$ x

Figure 4.39 and Figure 4.40 show the broken concrete production and the real time production rate of scale $\frac{1}{1440}$ x of which the total simulation time is 168.23 minutes. It required 109.36 minutes for all the 800 units to be produced. In this case, the *"Warm Up" Period* = 24.38 minutes, "*Up Running" Period* = 109.36 - 24.38 = 84.97 minutes and *"Cool Down" Period* = 168.23 - 109.36 = 55.88 minutes.

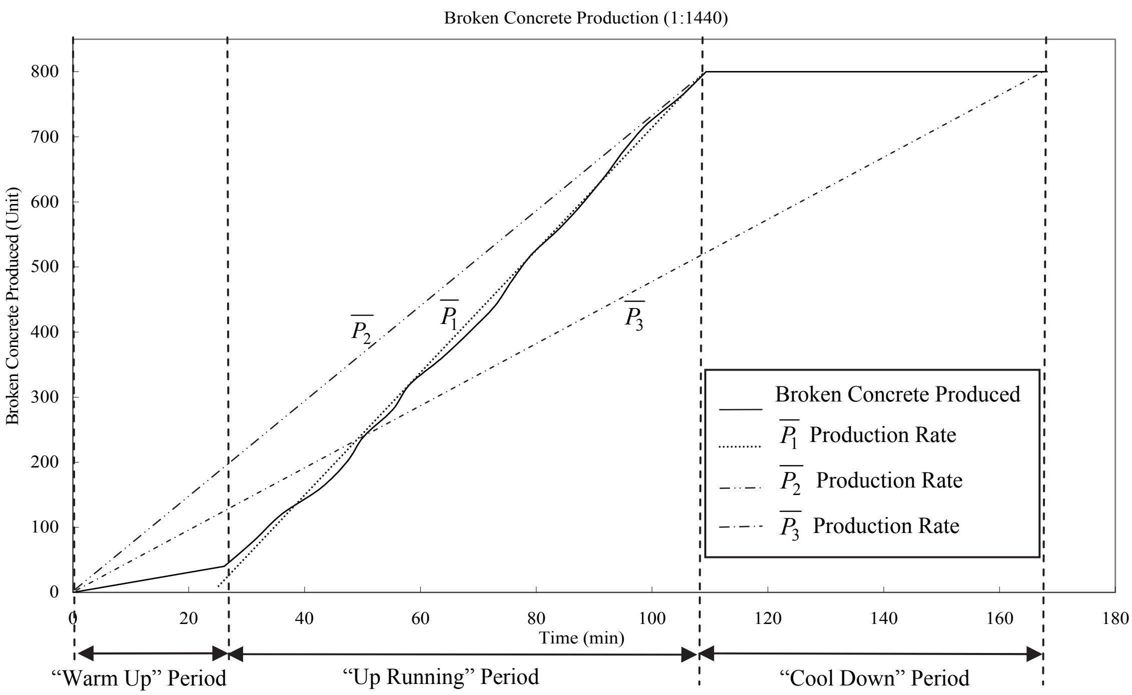


Figure 4.39. Broken Concrete Production against Time for Scale $\frac{1}{1440}$ x Model

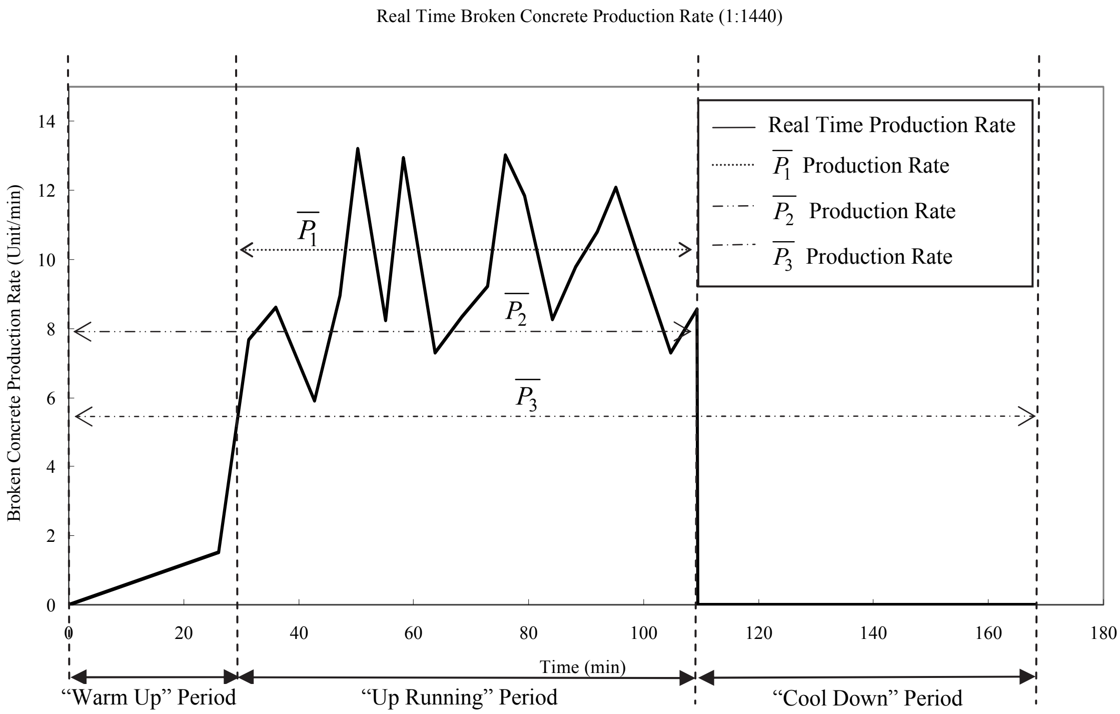


Figure 4.40. Real Time *BC* Production Rate against Time for Scale $\frac{1}{1440}$ x Model

T_1 = *"Up Running" Period* = 84.97 minutes

T_2 (production period) = *"Warm Up" Period* + *"Up Running" Period* = 109.36 minutes

T_3 (whole simulation time) = *"Warm Up" Period* + *"Up Running" Period* + *"Cool Down" Period* = 168.23 minutes

When the simulated production rate is calculated by dividing the Broken Concrete Produced in unit by P_3 (whole simulation time) in minutes, including both the *"Warm Up" Period* and the *"Cool Down" Period*, the result will be:

$$\frac{800\,\text{unit}}{168.23\,\text{min}} = 4.76 \text{ unit/min}$$

which is underestimated by a large amount.

Even if the average production rate is calculated by the period P_2, the simulated production rate will be the Broken Concrete Produced divided by P_2, and is equal to:

$$\frac{800\,\text{unit}}{109.36\,\text{min}} = 7.32 \text{ unit/min}$$

which is still unsatisfactory with the requirement.

The P_1 production rate is 9.41 unit/min after the *"Warm Up" Period* as obtained by fitting a trend line to the steady slope in P_1 period in Figure 4.39.

As the *"Warm Up" Period* and the *"Cool Down" Period* are constant, and the *production rate in "Warm Up" Period* is significantly lower than the P_1 production of the same time slot. Therefore, the smaller the simulation time is (the smaller the scale of the model to the actual system is), the lower its P_3 production rate is. Using P_3

production rate as simulated production rate may mislead the user by just dividing the simulation time by the scale $\frac{1}{1440}$x (multiplying by 1440) to estimate the total duration of the actual system.

In Figure 4.39, the curve starts in a gentle slope and climbs up to a steeper steady slope, which means the production rate is very low at the beginning stage and then becomes fully operated to give a constant P_1 production rate. When the linear trend line is fitted into the graph, the *"Warm Up" Period* is 24.38 min. The production in *"Warm Up" Period* is 40 units and the *"Warm Up"* production rate is equal to

$$\frac{40\text{unit}}{24.38\,\text{min}} = 1.64 \text{ unit/min}$$

When applying simulation model with small size to the estimate of the actual production rate, only P_1 production rate should be used to make a realistic approximation. However, P_1 production rate can only be obtained by setting up control variables and collect data from control report to analyze the simulated production rate. It is not recommended as data analysis is required and the result is not accurate.

4.6.5 Broken Concrete Production Rate with scale $\frac{1}{160}$x

Figure 4.41 and Figure 4.42 show the production and the real time production rate plot of model scale $\frac{1}{160}$x. The start and end portions refer to the *"Warm Up" Period* of 25.84 minutes and *"Cool Down" Period* of 47.88 minutes which are very closed to those of the model with scale $\frac{1}{1440}$x. However, the "*Up Running" Period* = 773.25 – 25.84 = 747.41 minutes which is nearly nine times that of model with scale $\frac{1}{1440}$x.

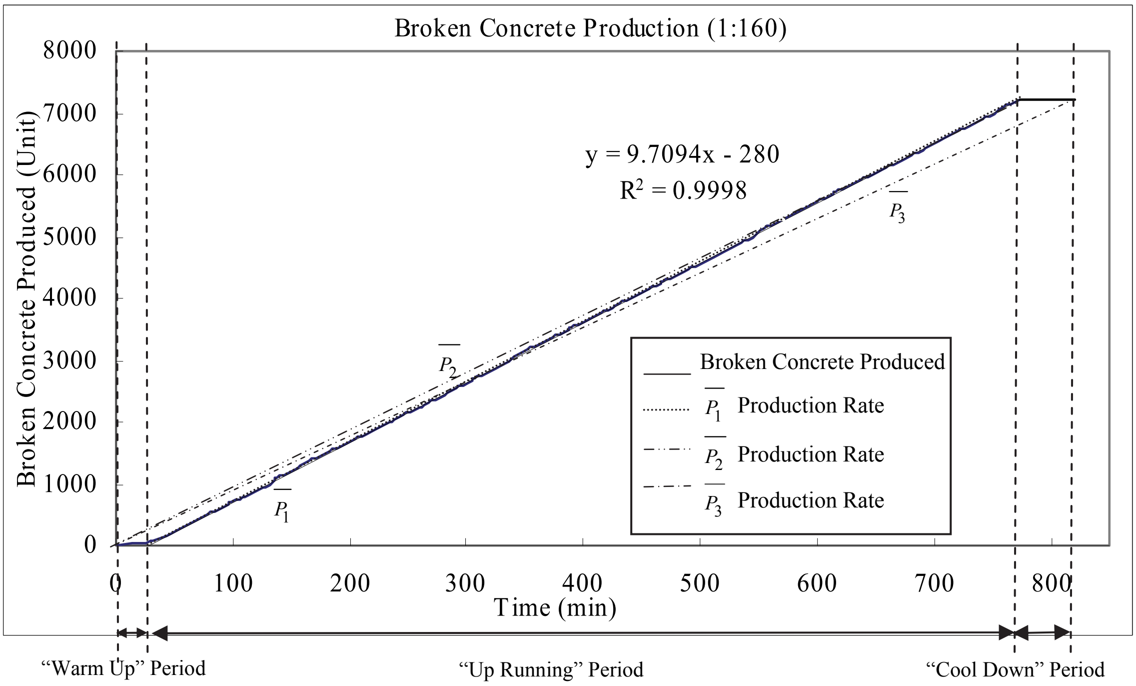


Figure 4.41. Broken Concrete Production against Time for Scale $\frac{1}{160}$ x Model

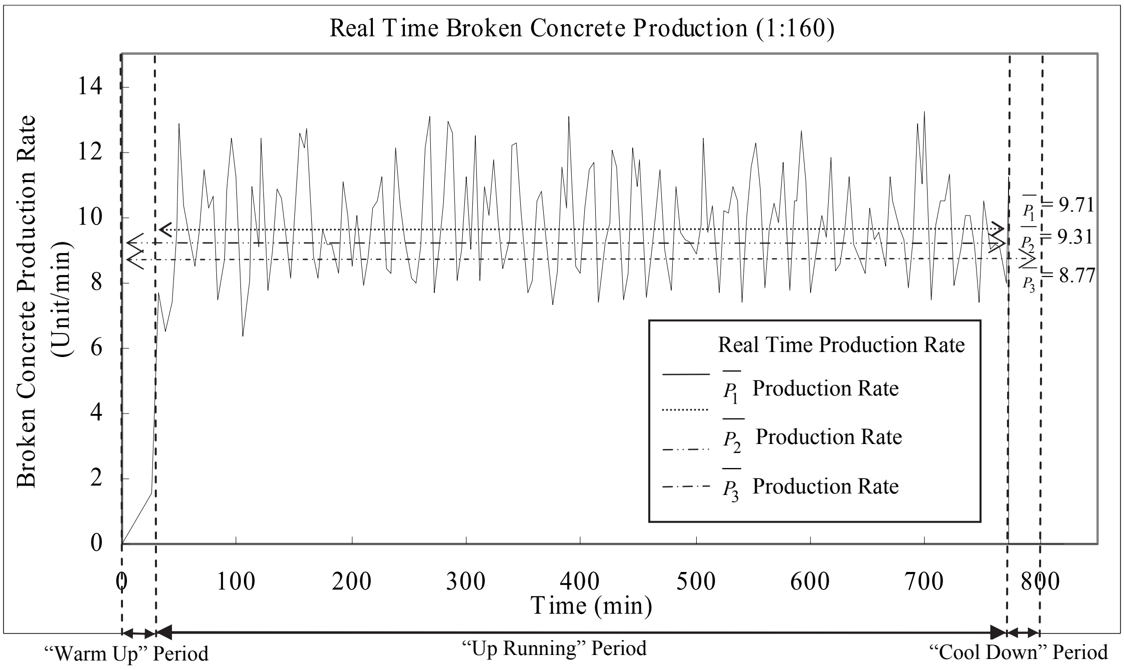


Figure 4.42. Real Time *BC* Production Rate against Time for Scale $\frac{1}{160}$ x Model

T_1 = *"Up Running" Period* = 747.41 minutes

T_2 (production period) = *"Warm Up" Period* + *"Up Running" Period* = 773.25 minutes

T_3 (whole simulation time) = *"Warm Up" Period* + *"Up Running" Period* + *"Cool Down" Period* = 821.13 minutes

The P_1 production rate is 9.71 unit/min, slope of trend line in P_1 period in Figure 4.41.

The P_2 production rate is $\frac{7200\text{unit}}{773.25\,\text{min}}$ = 9.31 unit/min

The P_3 production rate is $\frac{7200\text{unit}}{821.13\,\text{min}}$ = 8.77 unit/min

4.6.6 Broken Concrete Production Rates with scale $\frac{1}{40}$ x and $\frac{1}{10}$ x

Figure 4.43 and Figure 4.45 describe the broken concrete production of the models with scale $\frac{1}{40}$ x and $\frac{1}{10}$ x, Figure 4.44 and Figure 4.46 show the real time production rate of the models with scale $\frac{1}{40}$ x and $\frac{1}{10}$ x. The *"Warm Up" Period* and the *"Cool Down" Period* are insignificant in both scales. The P_1, P_2 and P_3 production rates converge locally (within a model) and globally (among the models) to steady state. The simulated production rate can be approximated as P_3 production rate. Therefore, the simulated production rate can be estimated directly by dividing the total amount of broken concrete produced by simulation end time with insignificant discrepancy.

The production rates of the models with different scales are summarized in Table 4.7

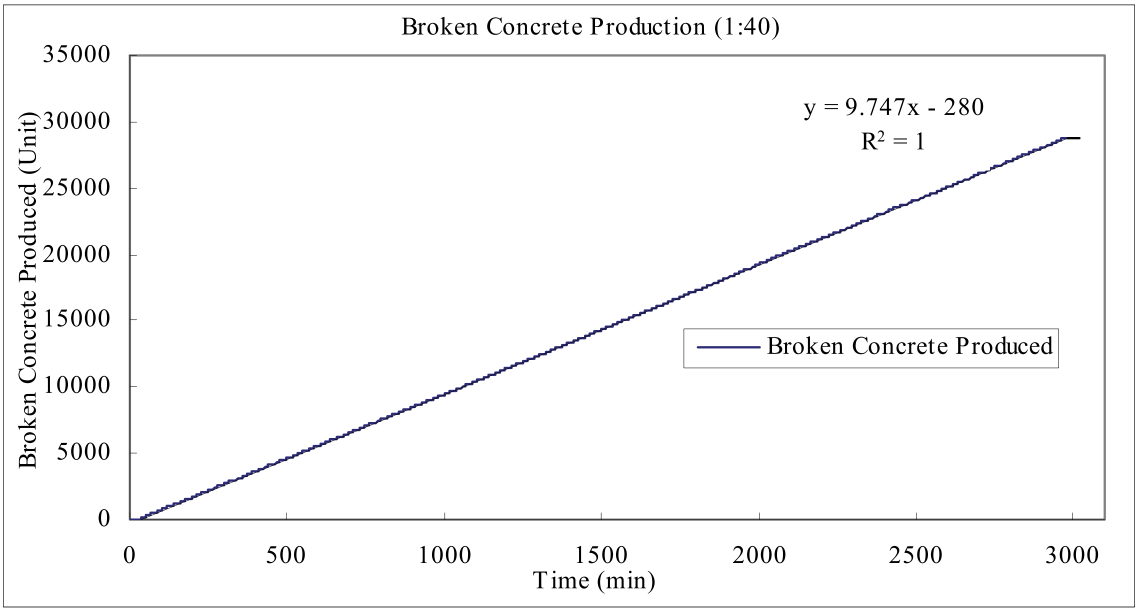


Figure 4.43. Broken Concrete Production against Time for Scale $\frac{1}{40}$ x Model

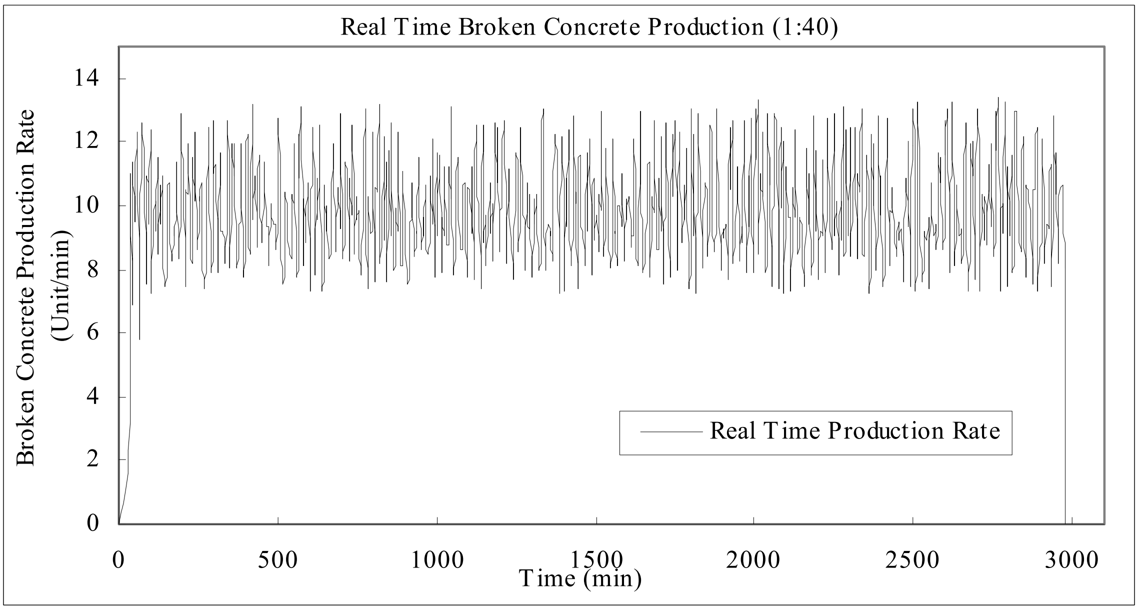


Figure 4.44. Real Time *BC* Production Rate against Time for Scale $\frac{1}{40}$ x Model

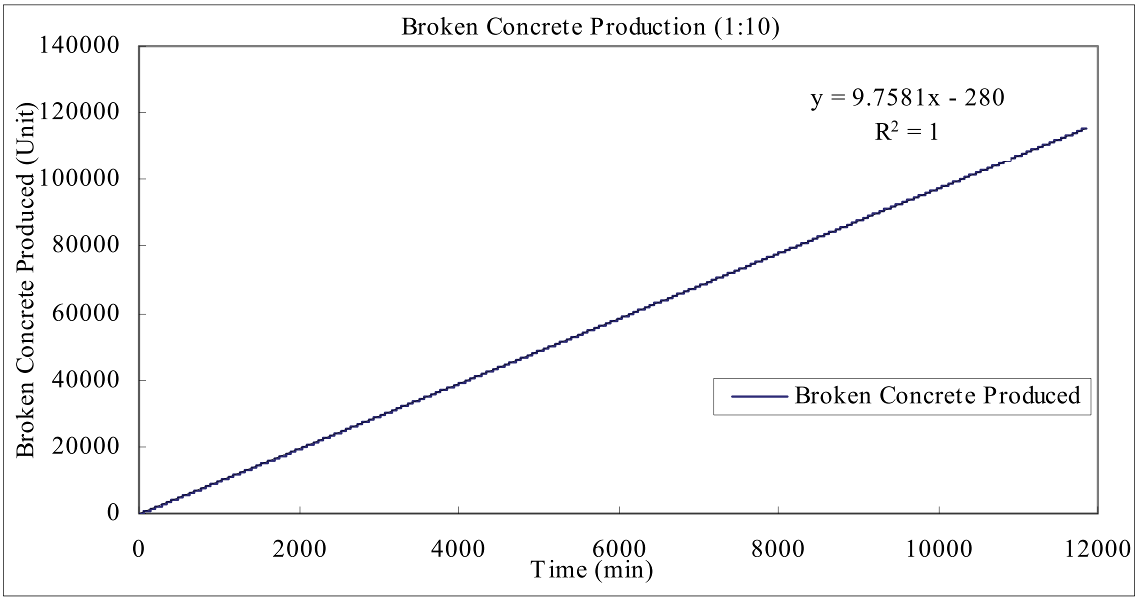


Figure 4.45. Broken Concrete Production against Time for Scale $\frac{1}{10}$x Model

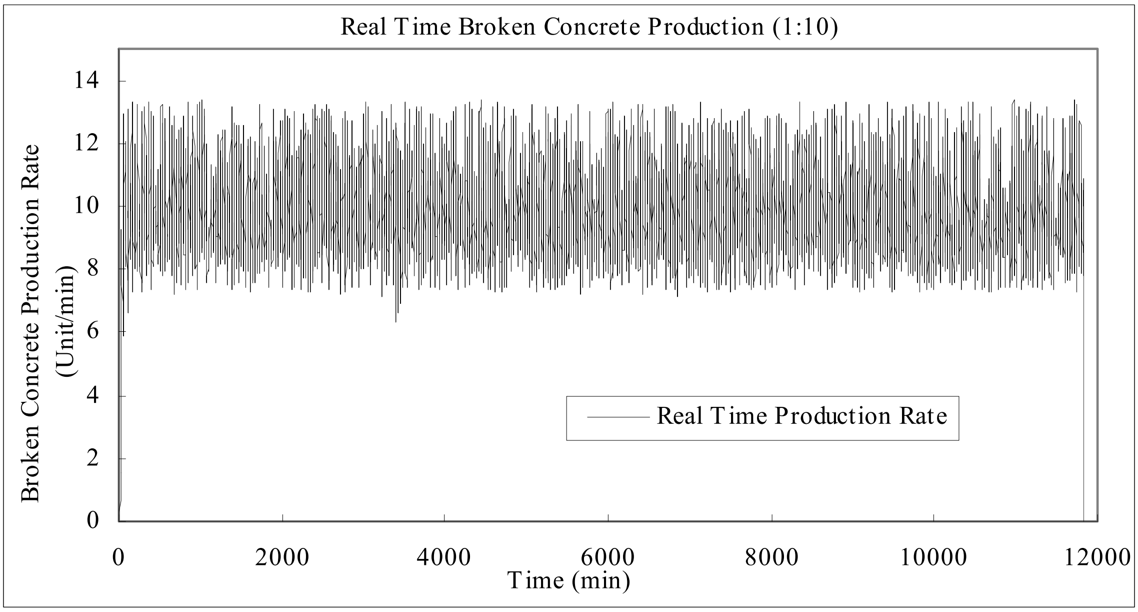


Figure 4.46. Real Time *BC* Production Rate against Time for Scale $\frac{1}{10}$x Model

Table 4.7. Production Rates and Process Time of Model of Different Scales

	Scale	**Broken Concrete Produced (unit)**	**Total Duration (min)**	**Process Time (h:m:s)**	**P_1 (min)**	**P_2 (min)**	**P_3 (min)**	**P_1 Production Rate (unit/min)**	**P_2 Production Rate (unit/min)**	**P_3 Production Rate (unit/min)**	**Actual/ P_3 Simulated Production Rate (unit/min)**
Actual	1:1	1154000	162240	-	-	-	-	-	-	-	7.11
Simulation	$\frac{1}{10}$ x	115200	11704	1:18:53	11813.19	11841.88	11880.54	9.76	9.73	9.73	9.73
Simulation	$\frac{1}{40}$ **x**	**28800**	**3017**	**0:04:59**	**2950.96**	**2979.69**	**3016.69**	**9.75**	**9.67**	**9.55**	**9.55**
Simulation	$\frac{1}{160}$ x	7200	821	0:00:20	747.41	773.25	821.13	9.71	9.31	8.77	8.77
Simulation	$\frac{1}{1440}$ x	800	168	0:00:01	84.97	109.36	168.23	9.41	7.32	4.76	4.76

4.6.7 Preliminary Tests Results

As shown in Figure 4.43, the model of the scale $\frac{1}{40}$ x provides a reasonable P_3 production rate to approximate the situation. The P_3 production rate is 9.55 unit/min, whereas the P_1 production rate is 9.75 unit/min with R^2 equals to 1. This model is a good fit enough to get statistical data and apply simulation in the different scenarios in the next section.

In scaling up the model to determine the duration required by the actual system, the best way is multiplying only the P_1 production rate by proportion instead of multiplying the whole simulation time. Otherwise, the actual production rate will be underestimated. It is because neither the *"Warm Up" Period* and the *"Cool Down" Period* with low production rate nor the zero production involvement will be magnified, leading to underestimate of the production rate.

However, the P_3 production rate of a model with a scale which is large enough can be approximated as the P_1 production rate of a model when the *"Warm Up" Period* and the *"Cool Down" Period* become negligible compared with the total duration. Depending on the accuracy required, the control variable *SPBC* can be used to monitor the P_2 (production period) instead of P_3 (whole simulation time), the *"Cool Down" Period* can even be eliminated.

Another way is to improve the *SDESA* model by allowing users to specify the start time of data collection, e.g. starting from the end of the *"Warm Up" Period* (Pidd 1998). This will give the same production rate as getting the results from the *"Up Running" Period* by monitoring the control variable.

4.6.8 Model Verification

The simulation result shows an ideal production rate under a working environment confined by the resource and technical constraints and some possible activities' interruptions with limited site records, whereas the actual production rate is affected also by environmental, human, managerial, political factors and unforeseeable uncertainties. In these case studies, data collection on waste management is found difficult to be obtained on sites where there was no one with designated responsibility for waste management, which was also confirmed by Guthrie (1999). However, the accuracy of the simulation highly depends on the input data. The more the information is obtained, the higher accuracy of the results can be achieved.

To compare the closeness of the simulation result and the site record, a "*Closeness*" factor is introduced and defined as the ratio between the *Actual Production Rate* and the *Simulation Production Rate*. The simulated production rate of the model of the scale $\frac{1}{40}$ x is used in the analysis as it will be used in the experiments in next section.

$$"\textit{Closeness}"\ \text{Factor} = \frac{\text{Actual Production Rate}}{\text{Simulated Production Rate}}$$

$$= \frac{7.71}{9.55} \times 100\%$$

= 80.73%

From the calculation, the simulation result shows 80.73 percent match with the actual situation. The difference between the simulation result and the actual situation refers to the above overlooked factors and contingent uncertainties and can be determined by subtracting the "*Closeness*" factor from one.

Additional Delay Factors = 1 - "*Closeness*" factor

= 1 - 80.73%

= 19.27%

Therefore, there exist some *Additional Delay Factors* which make the simulation result vary from the actual situation by 19.27 percent. When establishing the simulation model with limited information like this case study, a correction factor of $\frac{1}{80.73\%} = 1.24$ should be applied to the estimation of the project duration so as to account for the aforementioned risks that are not modeled in simulations.

4.7 Evaluating Cost Efficiency through Simulation

Under the assumption that there were no significant changes to the site layout and operation throughout the project period, the resulting simulation model provided a basis for 1) evaluating the cost efficiency of the site operation system and 2) estimating the total project duration and direct cost. Additionally, alternative scenarios of resource provisions were postulated, simulated, and compared. In each scenario, particular resources were added to the base model and the change to the total project duration was observed through computer simulation. Note, for a given scenario, the total project time and resource utilization rates were averaged from one hundred runs of Monte Carlo simulation. Table 4.8 shows the simulation-derived total project duration and direct cost estimation for each scenario, along with the resource provisions and their utilization rates. Note that in Table 4.8 the time and cost data represent the averaged simulation results from multiple Monte Carlo runs; and all the alternatives are arranged in a descending order by the total project duration.

Table 4.8. Simulation Results for Different Scenarios with Different Resources Available

Scenario ID	Additional Resources Description	Total Duration (Month)	Cost per day ($x10^3)	Total Cost ($x10^6)	Cost / Time Reduction ($/Day)	Quantity					Utilization Rate (%)				
						Backhoe	Truck	Breaker	Bulldozer	Cleaning Labour	Backhoe	Truck	Breaker	Bulldozer	Cleaning Labour
+1 TBHRDU	+1 Truck +1 Backhoe_ Raw Demolition Unit	9.69	32.5	8.19	N/A	8	7	2	1	4	79.6	78.1	99.7	99.0	80.4
+1 TTS	+1 Backhoe_Transfer to Sieve	9.68	30.7	7.73	N/A	8	6	2	1	4	69.8	79.9	99.6	99.1	80.2
Base Case	**Original Site Settings**	**9.67**	**29.2**	**7.35**	**0**	**7**	**6**	**2**	**1**	**4**	**79.6**	**78.9**	**99.2**	**99.0**	**80.2**
+1 BHRDU	+1 Backhoe_Raw Demolition Unit	9.67	30.7	7.72	N/A	8	6	2	1	4	69.7	78.9	99.2	99.0	80.2
+1 TRDU	+1 Truck_Raw Demolition Unit	9.67	31	7.80	3,870,135	7	7	2	1	4	85.5	68.5	99.7	98.9	80.3
+1 BDZ	+1 Bulldozer	9.67	31.8	8.00	N/A	7	6	2	2	4	79.6	78.9	99.2	49.7	80.2
+1 BHSP	+1 Backhoe_Stockpiling	9.66	30.7	7.72	2,670,195	8	6	2	1	4	69.7	79.8	99.4	99.1	80.4
+1 ST	+1 Backhoe_Sorting, +1 Breaker	9.66	31.1	7.82	1,833,490	7	6	3	1	4	79.6	79.3	66.5	99.0	80.3
+1 STBDZ	+1 Backhoe with Breaker +1 Bulldozer	9.66	33.7	8.47	4,363,636	7	6	3	2	4	79.6	79.3	66.5	49.6	80.3
+1 Critical	**+1 Backhoe_Stockpiling, +1 Backhoe_Sorting, +1 Breaker, +1 Bulldozer, +1 Backhoe_Raw Demolition Unit, +1 Backhoe_Transfer to Sieve**	**8.77**	**38.5**	**8.78**	**61,159**	**9**	**7**	**3**	**2**	**4**	**64.2**	**67.0**	**79.2**	**44.6**	**95.6**
1.5R	**1.5 x Resources**	**6.51**	**49.2**	**8.32**	**11,799**	**12**	**10**	**3**	**2**	**6**	**71.7**	**68.2**	**99.6**	**75.1**	**80.4**
2R	**2.0 x Resources**	**4.95**	**56.9**	**7.33**	**-163**	**13**	**12**	**4**	**2**	**8**	**84.4**	**72.2**	**99.4**	**98.5**	**79.9**
2.5R	**2.5 x Resources**	**4.04**	**76.9**	**8.08**	**4,990**	**18**	**16**	**5**	**3**	**10**	**69.8**	**48.3**	**99.3**	**57.2**	**80.0**

Note: Bold scenarios are economically-feasible alternatives

Critical resources in the site system were those with utilization rates over 90%. As for the original base case, the operation was smooth with utilization rates for resources of different types ranging from 78.9% to 99%. As seen from Table 4.8, providing one more resource unit for one or two types of critical resources alone would prove to be uneconomical (resulting in higher cost and longer duration) unless the provision of all the critical resources is scaled up simultaneously with a scale factor (such as 1.5x, 2x or 2.5x). Among all being assessed, four alternatives were identified as economically feasible as highlighted in Table 4.8: they are *Alternative "+1 Critical"* (adding one more unit to each critical resource in base case), *Alternative "1.5R"* (multiplying the quantity of each critical resource in base case by 1.5), *Alternative "2R"* (multiplying the quantity of each critical resource in base case by 2), and *Alternative "2.5R"* (multiplying the quantity of each critical resource in base case by 2.5).

In order to improve the cost efficiency of the overall system, providing more critical resources was justified only if the total project duration was considerably shortened. Next, the cost-time reduction ratio was calculated to compare each economically feasible alternative against the original base case so as to identify the best alternative. Note, the direct cost was dependent on equipment rental rates and the project duration, and was calculated in Hong Kong Dollars (1 USD = 7.8 HKD). The daily rates for major resources involved in direct cost estimation were obtained from a local equipment rental and sale company as listed in Table 4.9, which served as good references but did not represent the actual costs incurred by site contractors.

Table 4.9. Rental Rates of Major Resources Acquired from an Equipment Rental and Sales Company

Resource	**Cost per day (HK$)**
Backhoe with Breaker	1900
Backhoe with Operator	1500
Bulldozer	2600
Cleaning Labour	380
24-Ton Truck	1800

The first comparison was made between the *Base case* and *Alternative "+1 Critical"*.

$$\left.\frac{\Delta C}{-\Delta T}\right|_{(Original)\text{-}(1+Critical)} = \frac{\text{Total Cost of } Alt\ \text{“+1 Critical”} - \text{Total Cost of } Base}{\text{Total Duration of } Base - \text{Total Duration of } Alt\ \text{“+1Critical”}}$$

$$= \frac{\$\ (8.78\text{-}7.35)\text{x}10^6}{(9.67\text{-}8.77)\ \text{month x } \frac{26\ \text{day}}{1\ \text{month}}}$$

$$= \frac{\$1{,}430{,}000}{23.4\ \text{day}}$$

$$= \$61{,}159/\text{day}$$

The obtained ratio indicates that as of alternative "+1 Critical", shortening the total project time by one day would increase the total direct cost by $ 61,159. Similarly, the cost-time reduction ratio for *Alternatives "1.5R", "2R", and "2.5R"* were determined against the base case as follows:

$$\left.\frac{\Delta C}{-\Delta T}\right|_{(Original)\text{-}(1.5R)} = \frac{\text{Total Cost of } Alt\ \text{“1.5R”} - \text{Total Cost of } Base}{\text{Total Duration of } Base - \text{Total Duration of } Alt\ \text{“1.5R”}}$$

$$= \frac{\$\ (8.32\text{-}7.35)\text{x}10^6}{(9.67\text{-}6.51)\ \text{month x } \frac{26\ \text{day}}{1\ \text{month}}}$$

$$= \frac{\$970{,}000}{82.16\ \text{day}}$$

$$= \$11{,}799/\text{day}$$

$$\left.\frac{\Delta C}{-\Delta T}\right|_{(Original)\text{-}(2R)} = \frac{\text{Total Cost of } Alt\ \text{“}2R\text{”} - \text{Total Cost of } Base}{\text{Total Duration of } Base - \text{Total Duration of } Alt\ \text{“}2R\text{”}}$$

$$= \frac{\$\ (7.33\text{-}7.35)\text{x}10^6}{(9.67\text{-}4.95)\ \text{month x } \frac{26\ \text{day}}{1\ \text{month}}}$$

$$= \frac{-\$20{,}000}{122.72\ \text{day}}$$

$$= -\ \$163/\text{day}$$

$$\left.\frac{\Delta C}{-\Delta T}\right|_{(Original)\text{-}(2.5R)} = \frac{\text{Total Cost of } Alt\ \text{“}2.5R\text{”} - \text{Total Cost of } Base}{\text{Total Duration of } Base - \text{Total Duration of } Alt\ \text{“}2.5R\text{”}}$$

$$= \frac{\$\ (8.08\text{-}7.35)\text{x}10^6}{(9.67\text{-}4.04)\ \text{month x } \frac{26\ \text{day}}{1\ \text{month}}}$$

$$= \frac{\$730{,}000}{146.38\ \text{day}}$$

$$= \$4{,}990/\text{day}$$

It is noteworthy that *Alternative “2R”* (doubling the provision of all the critical resources) could shorten the total project duration while slightly reducing the total direct cost in comparison with the base case. This is because the total project duration could be cut short nearly by half from the original 9.67 months to 4.95 months. As a result, the total direct cost remained steady (with a marginal decrease from \$ 7.35 to \$ 7.33 million.) When the critical resource provision was multiplied by a factor of 2.5 (as in case of *Alternative “2.5R”*), the effect of cost increment would outstrip the magnitude of reduction in total project duration: one day shortened comes with a cost increment of \$ 4,999. Thus, although the total duration could be further reduced to 4.04 months, the total cost would rise to \$ 8.08 million by an appreciable margin of 10%. In regard to resource utilization rates in Table 4.8, *the base case* is the most efficient with all the resources having a working percentage over 78%. *Alternative "2R"* also shows high utilization rates of above 70% for all resources. Particularly, the backhoe utilization rate stands at 84.4%. This partly explains the high cost efficiency associated with this resource provision scenario. However, *Alternative "2.5R"* is less efficient as the utilization rates for bulldozer and truck resources are only about 50%.

Obviously, *Alternative "2R"* (i.e., doubling critical resource provision in the base case) is the optimum alternative to the present Kai Tak case. As shown in Figure 4.47, with increase of the scale factor for providing more critical resources, the total cost arrives at a minimum of $ 7.33 million at *Alternative "2R",* whereas the cost per day increases and the total project duration decreases. As for the optimum *Alternative "2R"*, the cost per day is about twice the value of the base case ($ 56,900 versus $ 29,200). As the Kai Tak site was large and open, it would be practically feasible to double the critical resource provision without causing congestion. Therefore, *Alternative "2R"* is identified as a better, feasible alternative provided that the project budget available could satisfy the higher cash flow requirement.

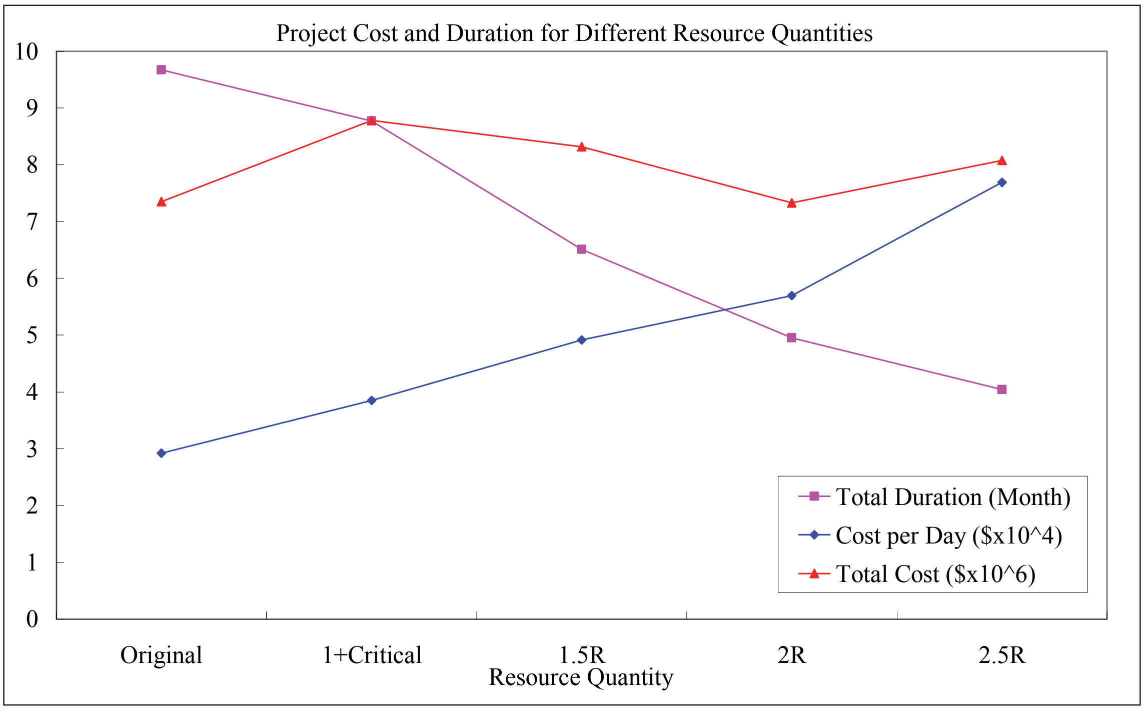


Figure 4.47. Project Cost and Duration Profiles for Scenarios with Different Resource Quantities

4.8 Discussion and Conclusions

This research has proved the feasibility of using operations simulation modeling techniques to investigate the cost efficiency of the selective demolition and waste handling practices. Based on modeling the site operation of broken concrete sieving and stockpiling in demolition of Hong Kong's Kat Tak Airport, the well-established construction simulation methodology of *CYCLONE* was contrasted with *SDESA*. The application framework specially developed for guiding the mapping and simulation of waste-handling processes was then implemented. A process flowchart was first developed, which served as convenient model input to facilitate quick generation of an operations simulation model by *SDESA*. The resulting simulation model rendered analytical decision support for contractors to evaluate time and cost parameters for a given waste-handling method. Taking the Kat Tak site for example, simulation experiments revealed 1) the actual site operation was smooth and efficient with utilization rates for resources of different types over 78.9%; 2) providing one more resource unit for one or two types of resources alone would result in higher cost and longer duration unless the provision of all the critical resources was scaled up simultaneously with a scale factor (such as 1.5x, 2x or 2.5x); and 3) doubling the critical resource provision in the base case would shorten the total project duration nearly by half (from the original 9.67 to 4.95 months), whereas the total direct cost would marginally decrease from HK$ 7.35 to HK$ 7.33 million.

This chapter demonstrates the computer application of the proposed formal framework for simulation approach and process mapping model in waste management. Different simulation models can be developed to compare the cost efficiency of different schemes in planning stages. It should be pointed out that the present research defines the cost parameter as the direct cost − direct construction resource usage on site. To address the need for sustainable development, the cost parameter can be broadened in the future research by considering more economical, social and environmental factors in cost benefit analysis for selective demolition practices. Examples are the social and environmental cost of virgin aggregates extraction; fossil fuel energy consumption in waste handling, transportation and recycling; and the social cost of demolition schedule upon businesses.

Chapter 5

Microtunneling Operations Simulations - So Kwun Wat Case

5.1 Introduction

On one hand, thanks to minimal impact to existing traffic and business and reduced environmental hazards, the emerging technology of microtunneling provides an appealing alternative to the conventional open trench method for construction and rehabilitation of subsurface utility pipelines in highly dense urban areas. On the other hand, technical complexities in site operations and variations in subsurface soil conditions could significantly extend the learning curve of implementing microtunneling, possibly undermining the potential productivity gain and hampering its wide application. This chapter shows the proposed formalized simulation modeling method to solve a case of microtunneling operations in Hong Kong. A twin micro-tunnel construction site offered a unique "test bed" for the simulation modeling.

Elaborate planning of a construction system of microtunneling and pipe jacking is crucial to smooth and efficient site operations. Trenchless technologies were widely adopted in Hong Kong during the past decades. Lau et al. (2008) described the uncertain factors and performance monitoring in trenchless construction operations. Mok et al. (2007) and Mok and Mak (2009) discussed the challenges in applying trenchless technologies in the urban area in Hong Kong. According to Chapman et al. (2007), planning of trenchless technology was found to be the most important area for future research. Many researchers have applied computer simulation to aid decision making for microtunneling construction (Sinfield and Einstein 1996, Ueki et al. 1999, Myers et al. 1999, Nido et al. 1999, Ruwanpura 2001, Ruwanpura et al. 2001, Ruwanpura and

AbouRizk 2001, Chung et al. 2004, Ruwanpura et al. 2004a, Ruwanpura et al. 2004b, Seneviratne et al. 2005, Luo and Najafi 2007 and Ruwanpura and Ariaratnam 2007). None of the above was applied for twin tunnel construction. The twin tunnel construction project in Hong Kong was adopted in this research as a unique "test bed" to implement operations simulation modeling in support of microtunneling construction planning. With high uncertainties in the ground conditions and the wear and tear of the disc cutters of the tunnel boring machine (TBM), it would be crucial to exercise comprehensive planning and risk management in microtunneling construction. Site management is essential in optimizing the site resources and delivery cycles. Lau et al. (2009) proposed a framework for development of intelligent decision support means to enable effective microtunneling construction planning. Lau and Lu (2010) established a simulation-based approach to planning the temporary traffic arrangement for microtunneling operations in urban areas. Lau et al. (2010) presented the way to plan pipe-jacking operations through simulation modeling based on a twin-tunnel microtunneling site.

The remainder of this chapter is organized as follow. A comparison between *CYCLONE* and *SDESA* models in the application to a case published by Luo and Najafi 2007 is shown Chapter 5.2. The background of an application case based on Hong Kong microtunneling site operations is given in Chapter 5.3. The simulation objective of the case study is defined in Chapter 5.4. The computer application of process mapping model is demonstrated in Chapter 5.5. The simulation model is validated in Chapter 5.6. Discussions and conclusions will be given in Chapter 5.7.

5.2 Comparison between *CYCLONE* and *SDESA* Models

Though *CYCLONE* has been around the scene since 1970s and numerous versions of *CYCLONE* software have been developed (the latest is the *Web-Cyclone* at Purdue University –cloud-like application), the concept and methodology are "timeless" and still widely used in construction academic programs throughout the world as the norm method for detailed construction process mapping, design and analysis. In a way, *CYCLONE* has become the universal communication tool and the established counterpart for cross validating new methods in construction simulation research.

With data collected from an actual microtunneling field study conducted at Louisiana Tech University, Luo and Najafi (2007) established a *CYCLONE* model to 1) identify major work flows, resources and activities involved in microtunneling and 2) represent the repetitive and interactive system logic by which various resources are matched and their flows are directed. Their base model was further embellished into a soil enhanced model, taking into account various soil compositions and different pipe jacking time in various types of soil. A linear regression of productivity against various soil compositions was obtained from simulation results.

According to the problem statement defined, the *CYCLONE* model (Figure 5.2) was duplicated and executed for 30 Monte Carlo duplications on *Web-CYCLONE* (Halpin et al. 2003). The *CYCLONE* model input is shown in Figure 5.1. An equivalent *SDESA* model (Figure 5.3) was built with the input model and the logical relationships between the operations are mimicked.

```
NAME LUO CASE LENGTH 3500 CYCLES 30

NETWORK INPUT
1 COM 'DISCHARGE & REFILL DESANDMAN' SET 1 PRE 14 18 33 FOL 14 18 24
2 COM 'MIX LUBRICATION' SET 2 PRE 13 22 32 FOL 13 21 22
3 COM 'DISMANTLE CABLES AND HOSES' SET 3 PRE 14 18 34 FOL 14 17 18 23 39 99
4 COM 'EMPTY SPOIL TANK' SET 4 PRE 19 20 31 FOL 19 20 27
5 COM 'PIPE SECTION PLACE ON GUARD RAIL' SET 5 PRE 14 18 21 23 24 27 29 35 FOL 14 18 41 42
6 COM 'LOWER SECTION INTO SHAFT' SET 6 PRE 18 30 FOL 18 29
7 COM 'ADJUST AIR GRIPPER' SET 7 PRE 13 14 26 FOL 13 14 15
8 COM 'INSTALL & CHECK AIR GRIPPER' SET 8 PRE 13 14 25 FOL 13 14 43
9 COM 'ATTACH SECTION TO CRANE' SET 9 PRE 13 15 16 17 28 FOL 12 13 40
10 COM 'BRING SECTION FROM STORAGE& INSTALL LINER CASING' SET 10 PRE 11 12 13 FOL 13 28 36
11 QUE 'SECTION ON STORAGE'
12 QUE 'POSITION AVAILABLE'
13 QUE 'LABOR A IDLE'
14 QUE 'SUPERVISOR IDLE'
15 QUE 'AIR GRIPPER READY' GEN 5
16 QUE 'CRANE IDLE'
17 QUE 'CONTROL CRANE'
18 QUE 'LABOR B IDLE'
19 QUE 'TRUCK IDLE'
20 QUE 'BACKHOE IDLE'
21 QUE 'LUBRICATION READY' GEN 4
22 QUE 'BETONITE READY'
23 QUE 'JACKING SYSTEM IDLE'
24 QUE 'WATER READY' GEN 4
25 QUE 'NEED AIR GRIPPER'
26 QUE 'GRIPPER NEED ADJUST'
27 QUE 'SPOIL TANK NOT FULL' GEN 4
28 QUE 'POSITION OCCUPIED'
29 QUE 'SECTION READY'
30 QUE 'SECTION READY'
31 QUE 'SPOIL TANK FULL' GEN 4
32 QUE 'NEED LUBRICATION'
33 QUE 'DESANDMAN READY TO DISCHARGE'
34 QUE 'SECTION IN PLACE'
35 QUE 'CABLE, HOSE, LASER READY'
36 FUN CON 5 FOL 25
37 FUN CON 4 FOL 32
38 FUN CON 4 FOL 31
39 FUN CON 4 FOL 33
40 NOR 'LIFT SECTION TO POSITION' SET 40 FOL 30
41 NOR 'CRANE RETURNS' SET 41 FOL 16
42 NOR 'JACK PIPE SECTION' SET 42 FOL 34 37 38
43 NOR 'DUMMY' SET 43 FOL 26 15
   PROBABILITY .333 .667
99 FUN COU FOL 35 QUA 1

DURATION INPUT
SET 1 TRI 10 12 15 SEED 485292067
SET 2 TRI 25 30 35 SEED 327188631
SET 3 BET 7 33 .643 3.02 SEED 434873927
SET 4 TRI 20 30 35 SEED 512022865
SET 5 BET 28 80 .761 1.841 SEED 376088551
SET 6 UNI 1 2 SEED 903203204
SET 7 UNI 10 15 SEED 910998027
SET 8 UNI 10 15 SEED 286021718
SET 9 DET 2
SET 10 TRI 2 5 15 SEED 510571571
SET 40 DET 1
SET 41 DET 2
SET 42 BET 12 102 .854 1.403 SEED 367640421
SET 43 DET 0

RESOURCE INPUT
30 'SECTION ON STORAGE' AT 11
1 'POSITION AVAILABLE' AT 12
1 'LABOR A IDLE' AT 13
1 'SUPERINTENDENT IDLE' AT 14
1 'AIR GRIPPER READY' AT 15
1 'CRANE IDEL' AT 16
1 'CRANE CONTROL' AT 17
1 'LABOR B IDLE' AT 18
1 'TRUCK IDLE' AT 19
1 'BACKHOE IDLE' AT 20
1 'LUBRICATION READY' AT 21
1 'BENTONITE READY' AT 22
1 'JACKING SYSTEM IDLE' AT 23
1 'WATER READY' AT 24
1 'SPOIL TANK NOT FULL' AT 27
1 'CABLES, HOSES, AND LASER READY' AT 35
```

Figure 5.1. *CYCLONE* Model Input of Luo and Najafi's Case

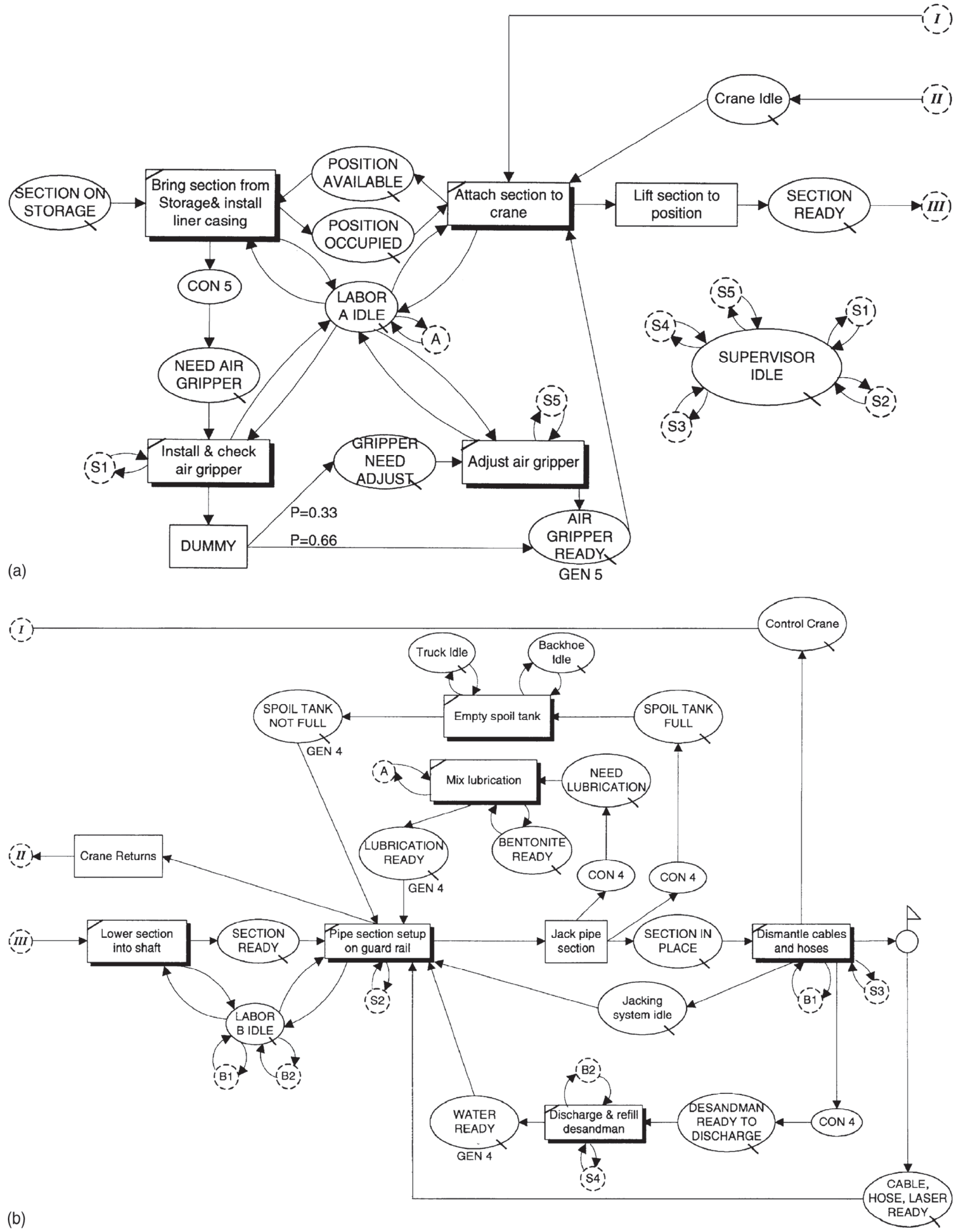


Figure 5.2. Prototype *CYCLONE* Model for the Observed Microtunneling Operation (Luo and Najafi 2007)

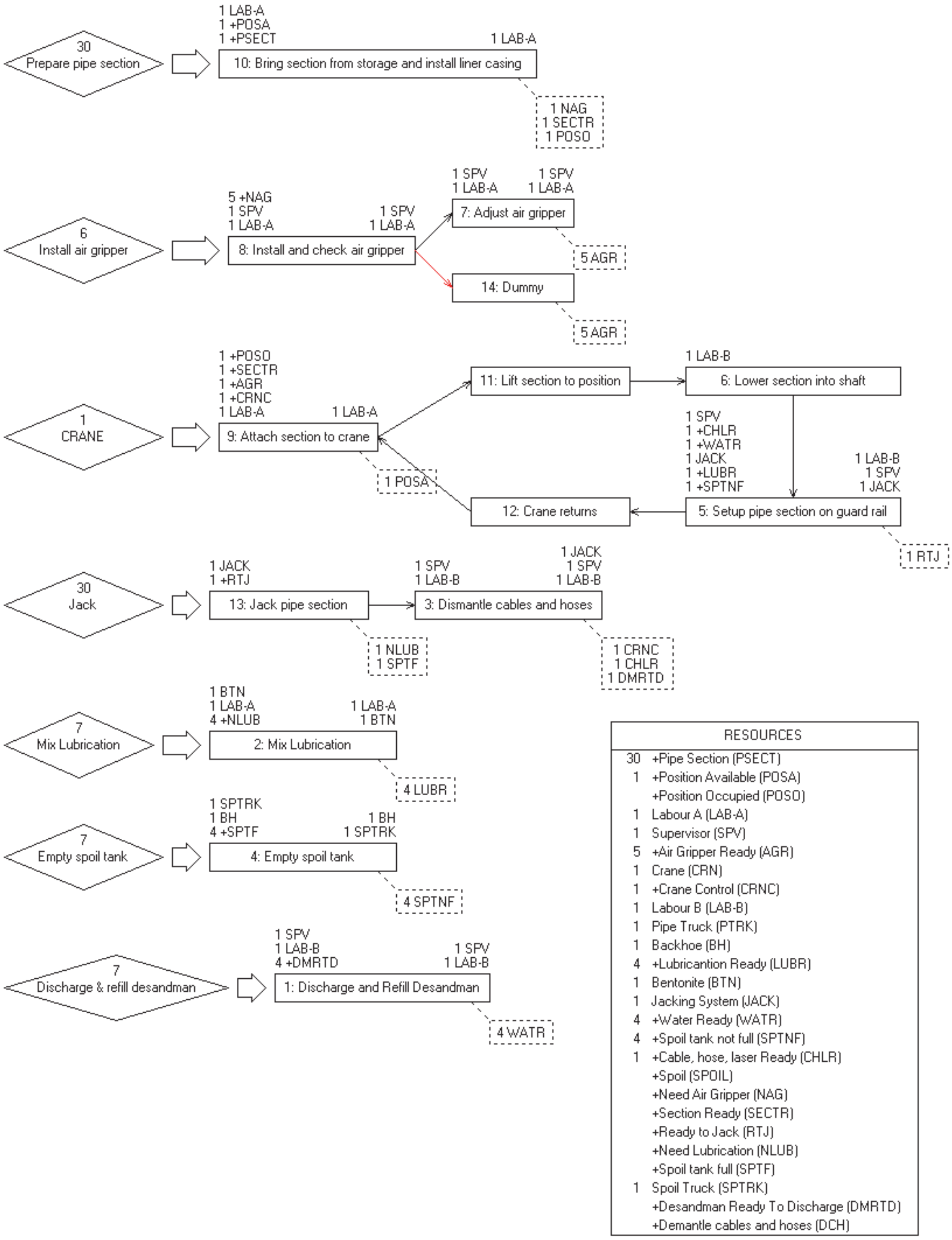


Figure 5.3. Equivalent *SDESA* Model of Luo and Najafi's Case

As shown in Figure 5.4, the patterns on cycle time over consecutive pipe sections from performing 30 simulation runs were derived on the authors' prototype model (basic

CYCLONE model without soil compositions). The mean cycle time for microtunneling each pipe section fluctuates around 110 minutes, bounded by the upper limit of 126 minutes and the lower limit of 92 minutes. The mean cycle time appears to be relatively flat, but roughly exhibits saw-shaped patterns: it slightly increases to a "saw tooth" and then smoothes out in every four sections (note those "saw tooth" points correspond with Section No. 5, No. 9, No. 13, No. 17, No. 21, No. 25 and No. 29 in Figure 5.4). Such a pattern can be properly explained by the system logic definition given in the *CYCLONE* model, that is: "the lubricant tank and the spoil tank last for the duration of jacking four pipe sections and the water in the system must be changed for four consecutive pipe sections." The cycle times for Pipe Section No. ($4n+1$, where n = 1,2,3,…) are longer because of those additional activities carried out after every 4th cycle. In addition, the simulation output analysis has resulted in an overall average of 110.3 minutes for installing one pipe section, in contrast with the 107.8 minutes benchmark obtained by the authors.

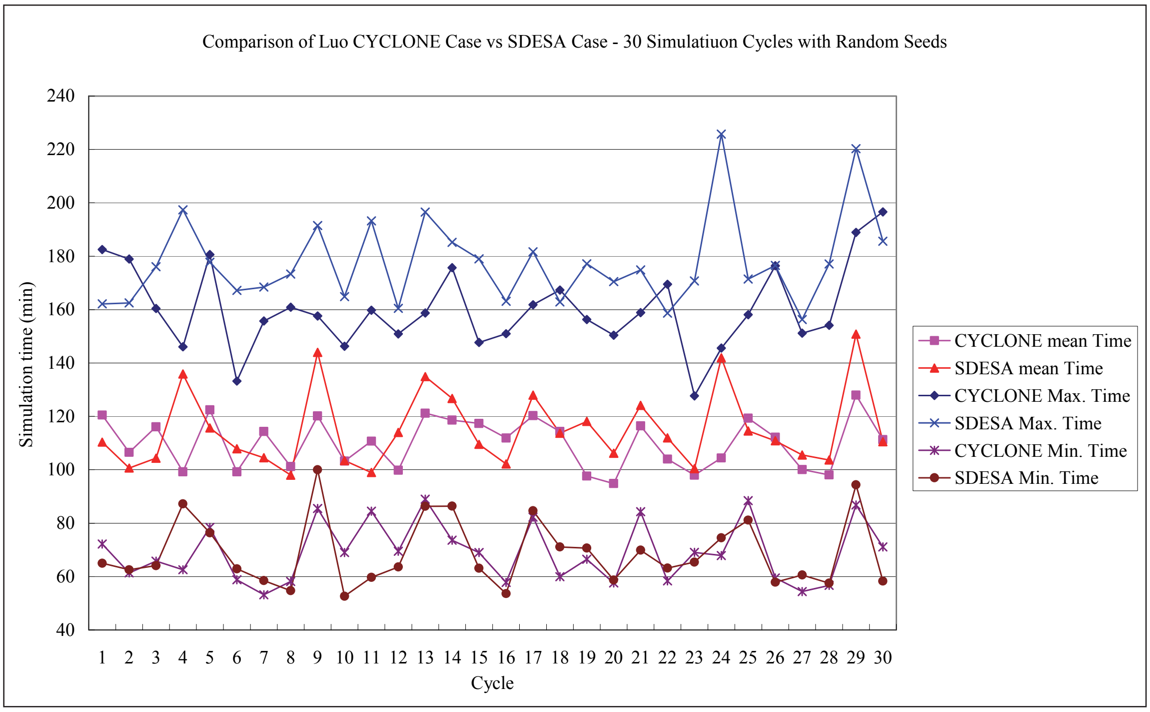


Figure 5.4. *CYCLONE* and *SDESA* Model Output of Luo and Najafi's Case

Also given in Figure 5.4 are the maximum and minimum cycle times for each pipe section, as recorded from the 30 simulation runs. The maximum and minimum cycle times exhibit similar patterns of change across pipe sections as previously observed on the mean cycle time. Note, the maximum cycle time roughly oscillates around the 170-minute mark on all pipe sections. This would be a useful pessimistic estimate of productivity when it is necessary to conjure up “worst-case” project scenarios.

The results are close with each other between the *CYCLONE* and the *SDESA* model output as shown in Table 5.1. In terms of the presentation of the model structure, the *CYCLONE* model is less readable, as the size of the model is so large that the “cycles” can no longer linked up. It is difficult to follow the defined “queue to combi” links and the links between the normal activities. On the other hand, the problem is much clearly defined in the *SDESA* model through five production lines and two cycle operations. Lu et al. (2009a) discussed the observations by Luo and Najafi against their own findings.

Table 5.1. Summary of *CYCLONE* and *SDESA* Model Output of Luo and Najafi’s Case

	CYCLONE	***SDESA***	**Percentage Difference**
Mean total time	3302	3452	4.5
S.D. of total time	139	154	10.8
Mean pipe section cycle time	110	115	4.5
Mean S.D. of pipe section cycle time	28	29	3.6

5.3 Background of Case Study

This research takes advantage of a twin tunnel project in Hong Kong as a unique “test bed” to implement operations simulation modeling in support of microtunneling construction planning. The first drive was taken as a “pre-drill” run in order to collect pipe-jacking cycle time data, map the main working processes being applied on site, and identify the practical constraints posed on the site operations and logistics. From the data plots over the drive length, the “jacking cycle” time distributions for different tunnel sections was fitted along the whole tunneling drive. So, the simulation model will adjust input models of the “jacking cycle” for the tunnel sections in planning a new job with similar design; in this case, the simulation model is applied on the second drive. In addition, delays and interruptions to the operations encountered in first drive can be also taken into account as potential risks in planning for the second drive by running the simulation model. The *SDESA* methodology and computer platform resulting from construction research are used in this study. The simulation model for the whole production system is presented and the application values of the simulation model for decision support is addressed with case studies.

With the development of mutual trust with the industry partners including the clients (Hong Kong and China Gas Company Limited and CLP Power Hong Kong Limited), consultant (Black & Veatch) and contractors (Kum Shing Construction Company Limited and Reliance-Tech Limited, a subsidiary of Chun Wo Development Holding Limited), this microtunneling site was adopted as a perfect field laboratory for the framework of simulation modeling and model verification.

5.4 Simulation Objective

The uncertainties in trenchless technologies imposed needs of comprehensive planning and risk management for the prevention of any prolongation of construction period that may incur liquidated damages and excavation permit extension fees based on the category of street really affected on site. The study targets at establishing a general algorithm for microtunneling operation simulation modeling approach and streamlining the site operations during the construction of utility tunnels. This project consisted of a twin-tunnel microtunneling at So Kwun Wat in Tuen Mun, N.T., Hong Kong that allowed for the implementation of the operations simulation modeling of microtunneling construction planning. For this unique “test bed”, the first drive was adopted as a “pre-drill” run for collection of microtunneling cycle time and soil data, working procedures at the site, and identification of practical constraints on the site operations and delivery cycles. Based on the data plots over the first drive length, the “jacking cycle” time distributions can be fitted into tunnel sections. The simulation model can then be updated for different “jacking cycle” time to optimize the delivery time. By minimizing the nuisance to the local residents and business and road users, the optimization of site operations is expected to further encourage the practice of trenchless technologies.

5.5 Computer Application of Process Mapping Model

As shown in Figure 5.5, the microtunneling project comprised twin tunnels of diameter 1200mm with a jacking length of 220 m across a 40 m wide nullah at So Kwun Wat. The twin sleeve pipes were laid 5 m underneath the river bed with horizontal separation of 2.2 m centre-to-centre apart. A bunch of power utility cable ducts and a bundle of domestic gas mains were installed after the completion of the twin tunnel construction.

Key locations in the site space are circled as location circles in the mapping process and listed in Table 5.2.

Table 5.2. Key Locations of So Kwun Wat Microtunneling Project

Site	**Location**
Remote Storage	Remote Storage
Site	Site Storage
Site	Shaft (Top)
Site	Shaft (Bottom)
Site	Tunnel
Site	Bentonite Storage
Site	Spoil Storage

Figure 5.5. Site Overview of So Kwun Wat Microtunneling Project

A HK$12 million-worth micro Tunnel Boring Machine (TBM) was adopted in both tunnel drives for the microtunneling construction. Each drive comprised 74 concrete pipe sections of 3 metre length. The microtunneling operations were carried out in late 2009. The jacking pit layout is shown in Figure 5.6.

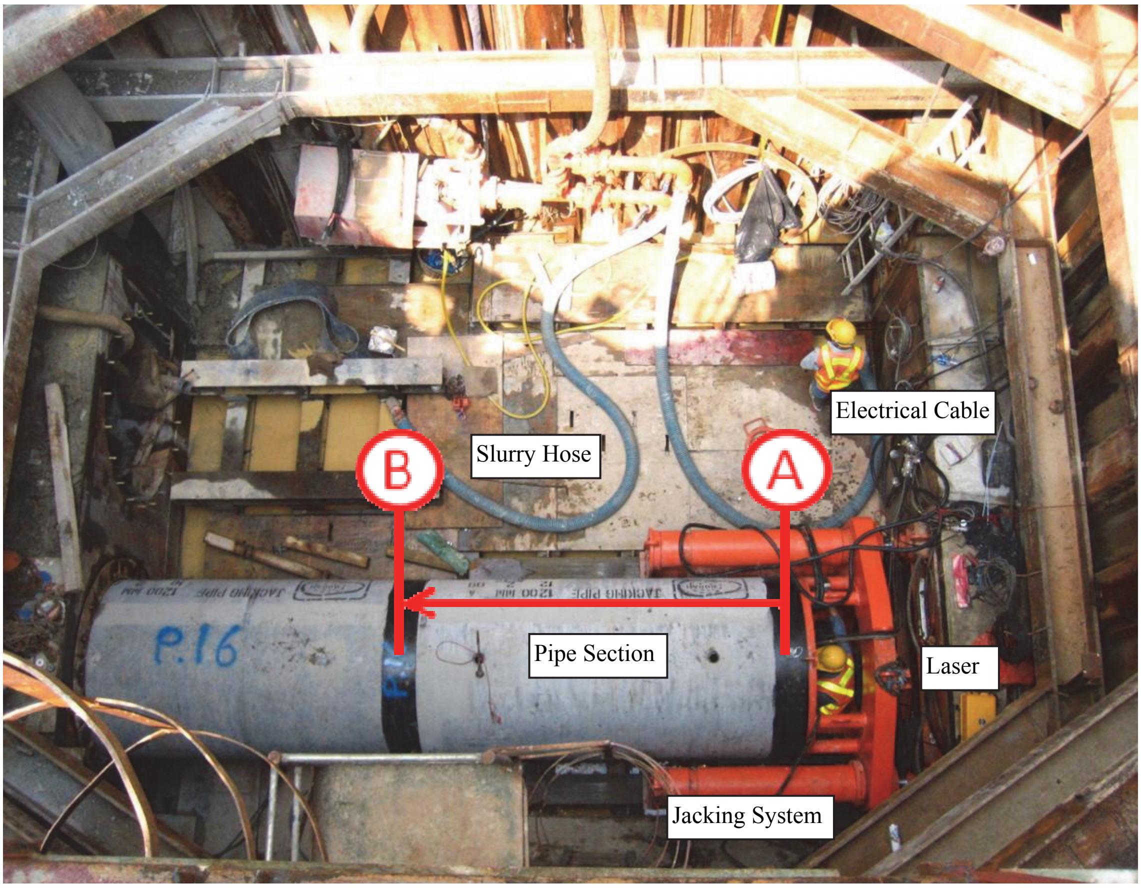


Figure 5.6. Jacking Pit Layout of So Kwun Wat Microtunneling Project

The site layout setting is shown in Figure 5.7. The key location circles are defined including the remote site storage, site storage, top and bottom of shaft and tunnel.

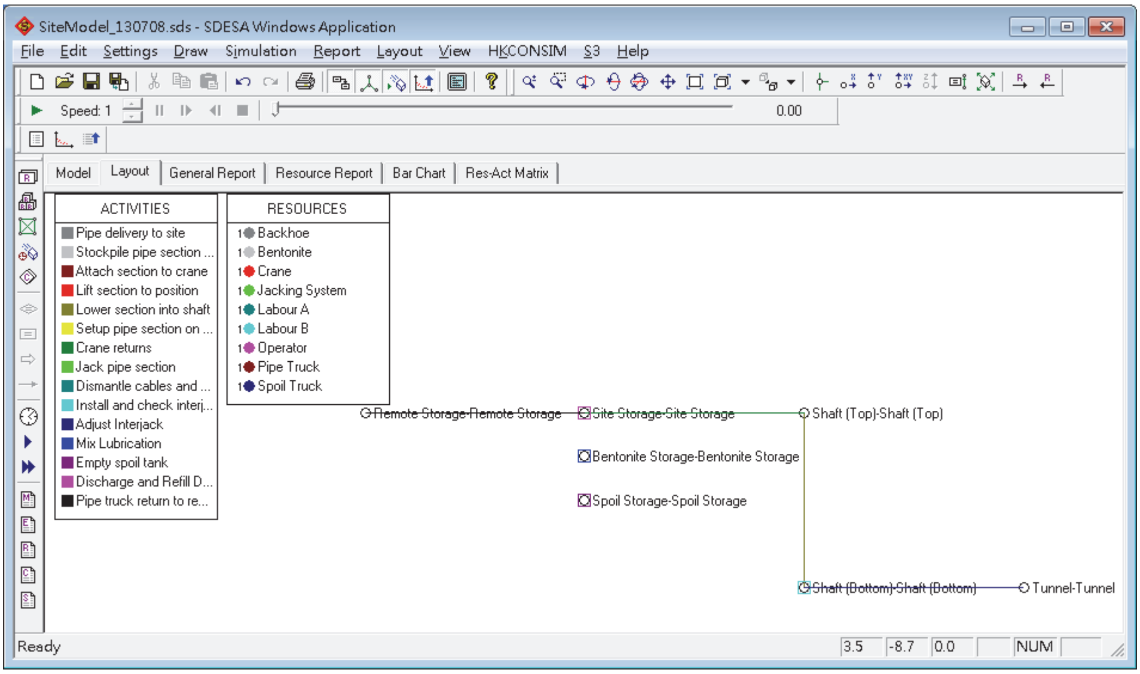


Figure 5.7. Site Layout Setting in *SDESA* Model

The site operations model formulated the logical sequences, resources and technical constraints based on the common activities at microtunneling sites. Further site-specific constraints could be modeled to tailor-make individual simulation cases.

At the planning stage, the simulation tool was used to investigate the effects of various combinations of resource allocation, pipe section delivery cycle time and site layout design. The statistical distribution of the pipe-section installation cycle time can inform detailed jobsite planning. Before the project commences, the project planner could borrow a typical microtunneling model template as a quick launch of simulation modeling. The simulation model is fine-tuned based on the actual site layout plan and estimated activity durations. Further site constraints such as the installation of a number of intermediate jacking stations for reducing total jacking force, and machinery breakdown are defined in the model.

Further simulation updating is necessary to assisting the construction planner in continuously revising the tentative completion date based on site information gathered. Once the model inputs are updated, the simulation experiments are conducted again to determine the remaining project duration and allocate the resources to synchronize system components.

During the construction stage, the operations information was collected for refining the accuracy of production rate prediction and project duration estimate. Distributions of the production time and non-production time were observed from simulation experiments for further site management.

Learning period was expected for the site establishment and the site operators to become familiar with the site conditions, tunnel alignment control and calibration of the subsidiary systems. The first two cycles for launching the micro TBM head and tail components were omitted from the operation data.

For the first drive, the micro TBM drove across highly varying geological conditions between Chainage (Ch.) 6m and 40m. A uniform sandy soil stratum existed from Ch. 40m to 105m, whereas hard materials were encountered between Ch. 105m and 220m. The cutter discs were found gradually deteriorating during the drive with two major maintenance operations carried out at Ch. 188m and 191m respectively for repairing the micro-TBM to an acceptable state before it can further proceed to the receiving pit at a reduced speed. The site operation data was chosen from Ch. 6m (pipe section No. 1) up to Ch. 182m (pipe section No. 58). The histogram of actual cycle time is shown in Figure 5.8.

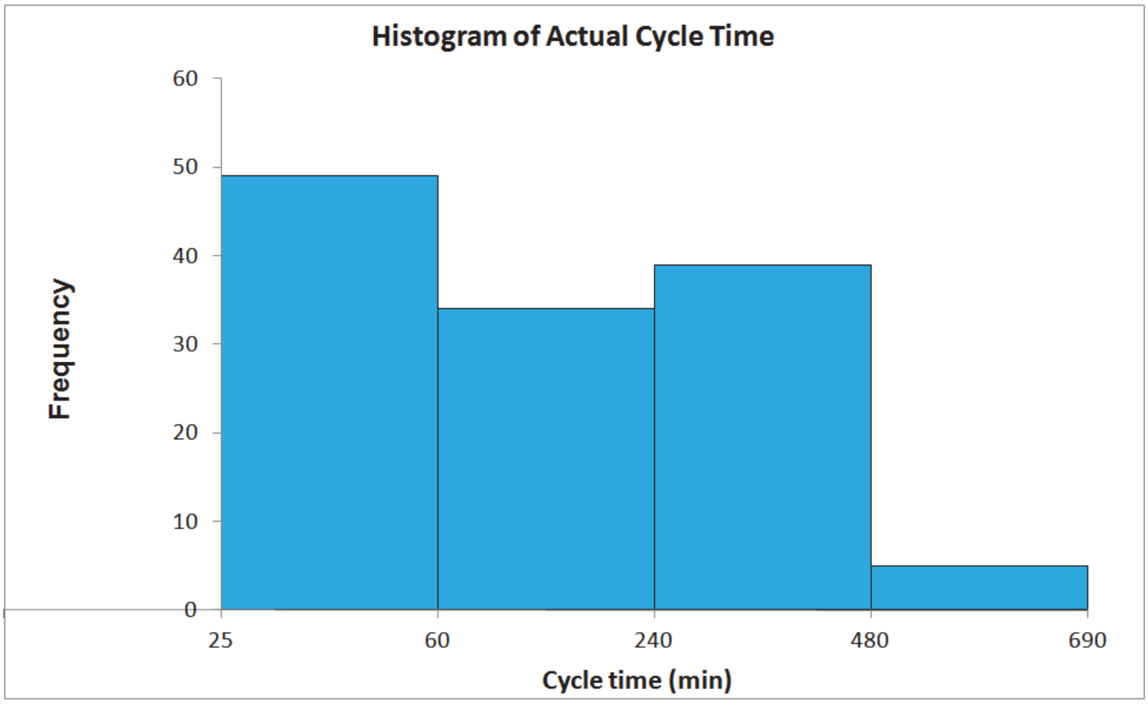


Figure 5.8. Histogram of Actual Cycle Time at So Kwun Wat Microtunneling Project

For the second drive, the micro TBM drove across a uniform silty soil stratum between Ch. 6m and 112m apart from some rocks encountered from Ch. 22m to 24m. Hard materials were found between Ch. 112m and 220m. The site operation data was chosen from Ch. 6m (pipe section No. 1) up to Ch. 199m (pipe section No. 63).

The site operations model consisting of logical sequence, activity duration, and resource allocation was defined during the site planning stage. The *"Jack"* work flow was the major work flow in the model and facilitated by other supporting work flows such as *"Mix Lubrication", "Empty Spoil Tank"*, *"Pipe delivery"* and *"Crane (lifting)"*. The duration for various activities is listed in Table 5.3. The stochastic activity durations for site operations were input into the model for statistical analysis of the overall production.

Table 5.3. Activity Definitions of So Kwun Wat Microtunneling Project

Work Flows	**Activities**	**Duration Input Model (min)**		
		Type	**L**	**U**
Pipe Delivery	Pipe delivery to site	Uniform	25	35
Unload Pipe Section	Stockpile pipe section to site storage	Uniform	2	4
Crane	Attach section to crane	Uniform	2	3
	Lift section to position	Uniform	1	2
	Lower section into shaft	Uniform	1	2
	Setup pipe section on guard rail	Uniform	30	60
	Crane returns	Uniform	1	2
Jack Pipe	Jack pipe section	Uniform	25	480
	Dismantle cables and hoses	Uniform	10	30
Install Interjack	Install and check interjack	Uniform	10	15
	Adjust interjack	Uniform	10	15
Mix Lubrication	Mix lubrication	Uniform	25	35
Empty spoil tank	Empty spoil tank	Uniform	20	35
Discharge and Refill Desandman	Discharge and refill desandman	Uniform	10	15
Pipe Truck to Remote Storage	Pipe truck return to remote storage	Uniform	15	25

Based on the site planning information, the simulation model can be established before the actual construction commencement. For this particular site located at a rural area, the site area was substantially large that plenty of pipe sections could be accommodated on site. This would relieve one of the major constraints - logistic delivery cycle - which may be much crucial for sites located at urban area. Different types of resources were defined in Table 5.4.

Table 5.4. Resource Pool for So Kwun Wat Microtunneling Project

Resource Class	Resource Type	Code	Amount
Moving Resources (MR)	Crane	Crane	1
Facilitating Resources (FR)	Backhoe	BH	1
	Bentonite	BTN	1
	Jacking System	JACK	1
	Labour A	LAB-A	1
	Labour B	LAB-B	1
	Pipe Truck	PTRK	1
	Supervisor	SPV	1
	Spoil Truck	SPTRK	1
Disposable Resources (DR)	Cable, hose, laser Ready	CHLR	1
	Crane Control	CRNC	1
	Desandment Ready to Discharge	DMRTD	0
	Interjack Ready	IJR	0
	Lubrication Ready	LUBR	4
	Need Interjack	NIJ	0
	Need Lubrication	NLUB	0
	Pipe Arrival	PARR	0
	Pipe Delivery	PDEL	4
	Pipe at Storage	PSTOR	2
	Pipe Truck Return	PTRKR	0
	Pipe Truck at Remote Storage	PTRKRS	1
	Ready to Jack	RTJ	0
	Stroage Vacancy	STORV	4
	Spoil tank not full	SPTNF	4
	Spoil	SPOIL	0
	Spoil tank full	SPTF	0
	Water Ready	WATR	4

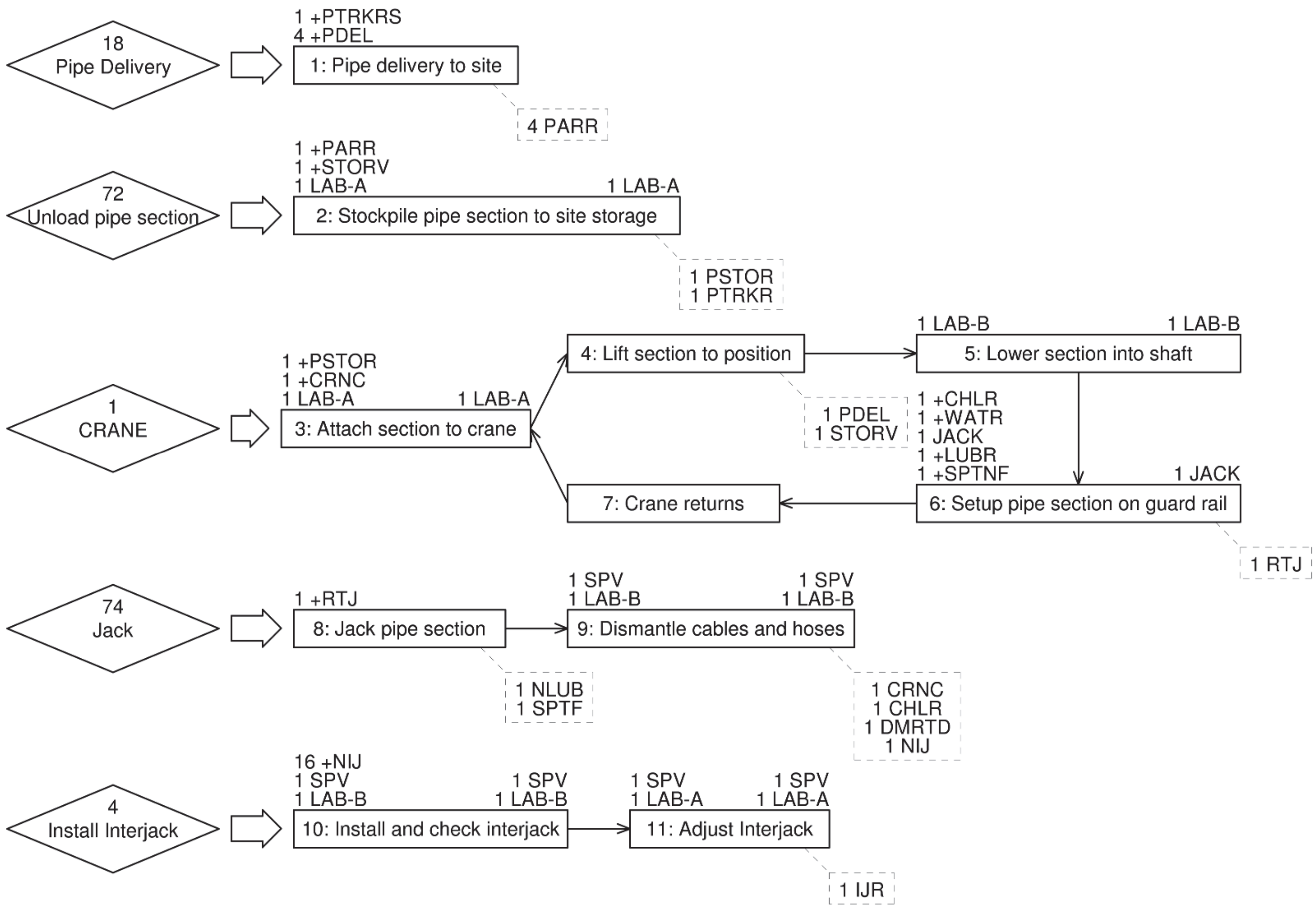


Figure 5.9. Total Model of So Kwun Wat Microtunneling Project in *SDESA*

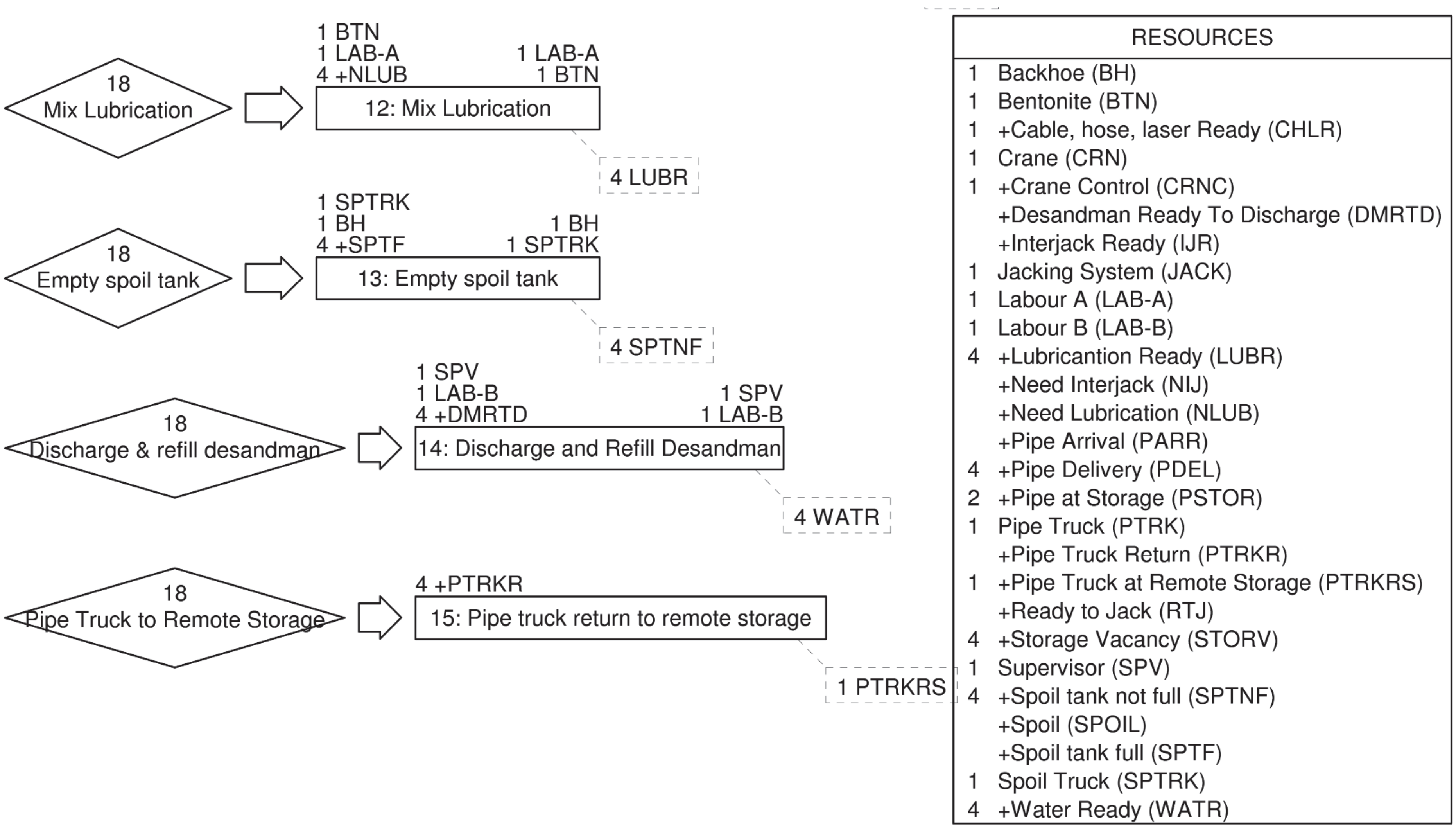


Figure 5.9. Total Model of So Kwun Wat Microtunneling Project in *SDESA* (con't)

After the pipe sections brought from remote storage site to the designated site storage area, the *labour A* (at-grade) would prepare the pipe section including visual inspection of the joints and installation of slurry lines in the pipe section. Once the micro TBM was installed and commenced the excavation, the pipe section would be attached to the crane and lifted into the shaft. *Labour B* (at the undercut) would then setup the pipe section on the guard rail including connection of slurry lines and electrical cables.

The main jacking operation would then commence. This activity would be the core part of this study and further discussed later. Upon the pipe section had been jacked into the ground, the slurry lines and electrical cables would be dismantled.

Some routine duties would be also carried out at the surface by *labour A* under the guidance of the *site supervisor*, for example, mixing lubricant, empty spoil tank, discharge and refill desandman. The installation of intermediate jacking stations would be installed at the specific location to be determined by the site engineer.

Figure 5.9 shows the overall simulation model based on the project method statement. Further activity durations can be updated when the site data is collected to revise the project forecasting. The flexibility of the simulation model allow for continuous updating of logical sequences and technical constraints when further information is acquired or site situation changes from time to time.

5.6 Model Validation

Figure 5.10 shows the cumulative distribution function (CDF) and statistical analysis of the model output for the total time of a single TBM drive. The simulation result shows that the mean duration for a single TBM drive of 220 m is 52 days plus or minus 0.7 days with 90% confidence interval. For this rural site, the site area is sufficient large and the spatial constraint for material delivery is insignificant. Four pipe sections can be delivered for each delivery cycle. The actual site stored even more pipe sections on-site.

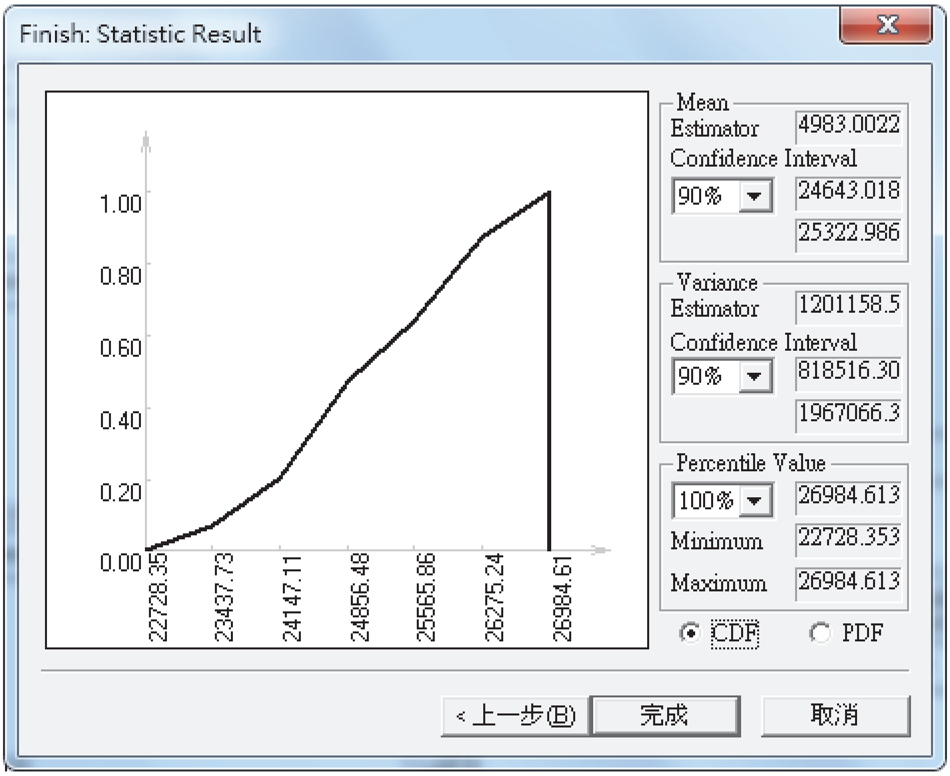


Figure 5.10. *CDF* and Statistical Analysis of Model Output: Total Time for Single TBM Drive

This simulation model forms a basic model that can be used as a platform for productivity analysis for urban sites based on different jacking cycle time, storage capacity and delivery time. With the assistance of simulation tools, the surface logistics management system can be optimized and the production line of the jacking operations can be streamlined. Spatial constraints could be introduced according to the maximum number of pipe sections to be stored on-site for those projects at the urban area. This would further pose a logistical constraint to the project planner to achieve a just-in-time delivery. Additional production analysis of microtunneling construction can be performed to determine the overall efficiency of site operations. The utilization rate of resources resulted from the model is shown in Table 5.5. The results show that the major resources are highly utilized.

Table 5.5. Utilization Rates of the Resources in So Kwun Wat Microtunneling Project

Resource	**Utilization Rate (%)**
Jacking System	89.3
Operator	96.5
Labour A	86.5
Labour B	96.0
Crane	15.6

Figure 5.11 shows the statistical output on resource utilization.

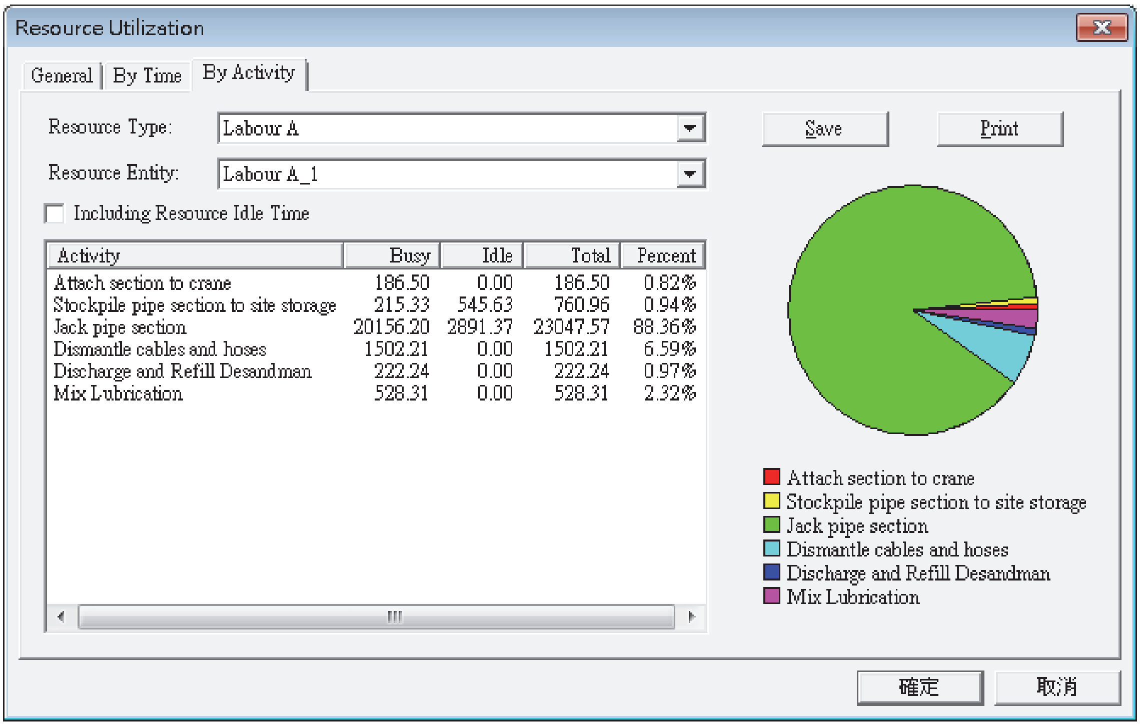


Figure 5.11. Statistical Output on Resource Utilization

Simulation models can render competent and reasonable decision support to the project planners in forecasting microtunneling production parameters.

5.7 Discussion and Conclusions

Elaborate planning of a construction system of microtunneling and pipe jacking is crucial to smooth and efficient site operations. This research takes advantage of a twin tunnel project in Hong Kong as a unique “test bed” to implement operations simulation modeling in support of microtunneling construction planning. The first drive was taken as a “pre-drill” run in order to collect microtunneling cycle time data and soil data, map the main working processes being applied on site, and identify the practical constraints posed on the site operations and logistics. From the data plots over the drive length, the “jacking cycle” time distributions were fitted for different tunnel sections defined by drilling length and soil types along the whole tunneling drive. So, the simulation model will intelligently adjust input models of the “jacking cycle” for the pre-mapped tunnel sections in planning a new job with similar geology and design; in this case, the simulation model is applied on the second drive. In addition, delays and interruptions to the operations encountered in first drive can be also taken into account as potential risks in planning for the second drive by running the simulation model. Working closely with industry partners, this microtunneling site provides a perfect field lab for simulation modeling and verification. The *SDESA* methodology and computer platform resulting from construction research are used in this study. The simulation model for the whole production system is presented and the application values of the simulation model for decision support is addressed with case studies.

This chapter demonstrates the computer application of the proposed formalized simulation modeling method for a microtunneling project. The simulation results showed a good match with actual site performance. With the general simulation framework, different simulation models can be developed to solve many engineering problems in project planning and operation stages. In conclusion, simulation assists in addressing complexities and uncertainties associated with productivity study of microtunneling pipelines in subsurface infrastructure engineering. Nevertheless, the validity of simulation sits on three pedestals, namely, 1) input modeling, 2) system logic representation, and 3) statistical analysis of output. Thus, development and verification of a simulation model, along with follow up virtual experiments based on simulation, demand rigor, insight and patience to ensure soundness on all three pedestals.

Chapter 6

Combined Modeling Approach

6.1 Introduction

This chapter addresses the issue of how to model the production capacity of a "continuous" plant in a predominantly discrete construction system by using discrete event simulation. A plant of continuous nature relies on a material-handling mechanism (such as conveyor or pipeline) to continuously convey and process material delivered in "discrete" truck loads. In contrast with discrete resources commonly encountered and matched in construction (such as a truck, an excavator, and a crane), a buffer is the hallmark of a continuous plant (such as unloading container); and one or multiple feeder resources (trucks) can be simultaneously processed subject to the production capacity of the plant. With a concrete pump example, the potential pitfall of simplifying a continuous plant as one discrete resource entity is discussed. Then, a method for modeling a continuous plant with a finite quantity of discrete resource entities in simulation of a predominantly discrete system in construction is formalized. A practical application of modeling the production capacity of a magnetic separation plant in iron mining operations will be described. The remaining chapter is organized as follow. The background of combined modeling approach is described in Chapter 6.2. The problem statement is defined in Chapter 6.3. The literature of combined modeling approach is reviewed in Chapter 6.4. Continuous plant discretization is proposed in Chapter 6.5 and practical applications are given in Chapter 6.6. Conclusions are drawn in Chapter 6.7.

6.2 Background

Simulation modeling builds a logical model on the computer medium as a valid, adequate representation of a complicated problem in reality, aiming at achieving a better understanding of the problem and hence resolving the problem. (Law and Kelton 2000) With respect to the mechanism by which the state of the system changes over time, simulation methodologies can be broadly categorized into discrete event simulation and continuous simulation (Prisker and O'Reilly 1999).

In discrete event simulation, the modeler is concerned with how to describe the logical conditions for triggering the occurrence of events that change the system state only at discrete points in time. The majority of simulation applications in construction engineering fall into the discrete class for its simplicity and effectiveness (Shi and AbouRizk 1998.) Therefore, discrete event simulation provides the norm viewpoint for representation of a construction operations system into a simulation model. *CYCLONE*, along with its later extensions and add-ons, is the best-known discrete simulation method used in construction engineering research.

As regarded continuous simulation, the state variables of the system change continuously with time and such changes are characterized into a set of differential equations. Simple differential equations can be solved analytically, thus, the values of state variables can be integrated against time based on their initial values. However, solving many continuous models needs resort to numerical analysis techniques (e.g. Runge-Kutta integration) in order to evaluate the state variables at a particular point of time (Law and Kelton 2000.) One of the continuous simulation applications in the construction domain was to model the drawdown of underground water table over time as a result of construction site dewatering operations by a system of pumps (Hajjar et al 1998.)

In simulation of practical construction systems, certain elements − within a predominantly discrete system are continuous in nature − being resources or processes. Modeling such systems involves both discrete and continuous simulations, resulting in the hybrid viewpoint of combined simulation (Law and Kelton 2000). The dependent variables may change discretely, continuously, or continuously with sudden jumps, contingent on the occurrence of time events or state events. The key characteristic of the combined simulation paradigm lies in the interactions between system variables with respect to the following aspects: 1) a continuous variable may take a discrete change in value at a time event; 2) an event involving a continuous state variable reaching a threshold value may trigger the occurrence of an event; and 3) the functional description of continuous variables may be altered at discrete times (Pritsker and O'Reilly 1999). Commercial discrete-event simulation packages provide the functionality for incorporating continuous elements into a discrete system model. In particular, the *SLAM/AweSim* system (Pritsker and O'Reilly 1999) has been used for combined simulation in construction research.

In order to estimate the effect of weather on productivity and duration of weather-sensitive activities, a combined discrete-event/continuous simulation was to link the continuous weather parameters with the discrete-event project scheduling model by integrating the use of *SLAM* simulation platform, *MS Project*, and *NeuralWindows* (AbouRizk and Wales 1997). Based on the *SLAM* simulation platform, a continuous simulation model and a discrete simulation model were independently developed and contrasted for a pipeline project (Shi and AbouRizk 1998). Note the continuous model defines a set of differential equations to represent the continuous progress of consecutive activities on the project, whereas the discrete operations model depicts the resources' construction cycles in detail. The comparison concluded that the discrete model provides more flexibility while entailing less difficulty than the continuous model.

6.3 Problem Statement

In a predominantly discrete construction system, a continuous plant features a material-handling mechanism (such as conveyer or pipeline) that continuously conveys material − delivered by transit resources (such as trucks or mixer trucks) − to a designated location in the site. A discrete batch of material is not readily identified and easily observed in the material handling process by a continuous plant. A plant of continuous nature has a limited production capacity in terms of the quantity of material processed in a time unit (hour or day). A continuous plant often constitutes the "bottleneck" resource in a site production system, driving the configuration of other supporting resources and controlling the overall productivity performance. For the continuous plant like pump, its production capacity is implicit if discrete modeling is applied.

Let us consider a case of a concrete pump equipped with a feeder container and pipelines, which continuously pumps concrete from the unloading point − where mixer trucks are unloaded − to the concrete-placing point situated on the floor being built. In this case, the concrete pump can be seen as a continuous plant. In contrast, if a tower crane is used to pour concrete, a skip-load of concrete can be readily identified and tracked as a discrete batch of the material being handled. Thus, the material flow in concrete pouring is not continuous, nor is the crane a continuous plant. Other examples of continuous plants include 1) an aggregate production plant with a conveyor system to process truck loads of raw material into aggregates of various sizes in continuous flows; 2) an iron ore processing plant with magnetic separation drums for extracting iron sand from the slurry of iron ore (Lu et al. 2007b, Lau et al. 2014); and 3) a road section for carrying urban traffic flows which include construction trucks delivering precast pipe sections to a microtunneling and pipe jacking site (Lau et al. 2010, Lau et al. 2013). Lau et al. (2011) further proposed the integration of construction and traffic engineering in simulating pipe-jacking operations in the urban areas.

6.4 Combined Modeling Approach

Apparently, the "continuous plant" problem can be tackled with a combined modeling approach. On one hand, the plant production rate function is defined for continuous modeling, which is integrated over the simulation time to derive the production output. On the other hand, the production cycle of trucks (arrival, waiting, unloading, and returning to batching plant) is modeled by discrete event simulation. A combined simulation executive program seamlessly blends the two simulation paradigms during dynamic execution of the simulation model.

However, the downside of a combined simulation approach resides in the expense of additional time spent in developing a detailed model (AbouRizk and Wales 1997). For instance, beyond developing a diagrammatic model by connecting basic *SLAM* modeling elements, Shi and AbouRizk (1998) inserted *FORTRAN* code as the *SLAM* subroutines written to realize continuous modeling of two repetitive pipeline construction activities. They pointed out that modeling resource sharing among activities is less straightforward in a continuous model, and observed *"the major modeling functions in a continuous model have to be coded by the user, making continuous simulation more difficult to implement."*

Hence, the problem statement for the present research is simple: in a predominantly discrete operations system, is it possible to devise a quick yet valid method for modeling the production capacity of a continuous plant with discrete resource entities? As such, applying the discrete simulation method (such as *CYCLONE*) is sufficient and accurate to simulate the complete operations of construction. This would not only add to the usefulness and flexibility of a discrete simulation methodology, but also help reduce the application cost of construction simulation methods in terms of software expenses and learning efforts.

6.5 Continuous Plant Discretization

Herein, a straightforward methodology is proposed for discretizing a continuous plant in a discrete simulation model of construction operations. First, the potential pitfall of modeling a continuous plant by simplifying it as one discrete resource entity is discussed. An illustration of combined modeling is shown in Figure 6.1. Discrete events occur at time T_1, T_2 and T_3 respectively, whereas continuous event occurs at time t_1, t_2, … , and t_i.

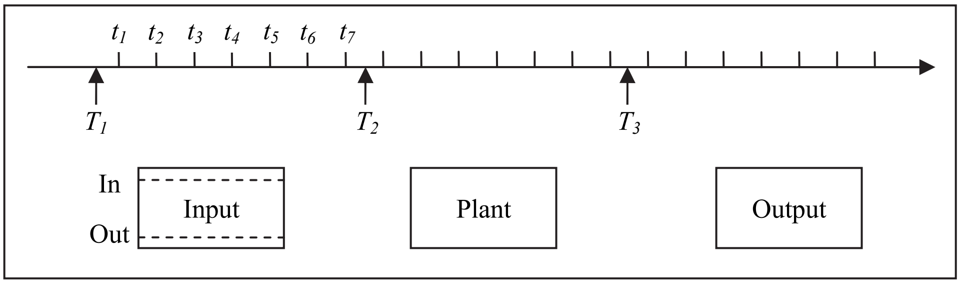


Figure 6.1. Combined Modeling

Some criteria are defined for common continuous plant. *U* is the *flow in threshold* control the loading trucks to switch *"In"*, whereas *L* is the *flow out threshold* control the loading trucks to switch *"Out"*. The *Switch_In* status is equal to 0 when the plant is nearly full, no further loading activity is allowed; it is equal to 1 when the plant is not full, loading activity is activated. The *Switch_Out* status is equal to 0 when the plant is nearly empty, no processing activity is allowed; it is equal to 1 when the plant is not empty, processing activity is activated. Table 6.1 shows the conditions and the corresponding activation of events.

Table 6.1. Conditions and Activation of Events

Conditions	**Activation of Events**
If Switch_Out = 1	Then $Q_{\Delta t} = \int_0^{\Delta t} P dt$; and $Q_{Tot} = Q_{Tot} + Q_{\Delta t}$
If $Q_{Tot} \leq L$	Then Switch_Out = 0
If Switch_In = 1	Then check discrete calendar for loading event: $Q_{Tot} = Q_{Tot} + Q_{\Delta t}$
If $Q_{Tot} \geq U$	Then Switch_In = 0
If $Q_{Tot} > L$	Then Switch_Out = 1
If $Q_{Tot} < U$	Then Switch_In = 1

Q_{Tot}, Switch_In and *Switch_Out* serve as "global" control variables between continuous and discrete simulation executives. As long as Q_{Tot} changes, it is required to check two switches. The logic control between two executives can be entrapped such that the simulation is stuck. How two simulation executives internal is a black box.

This research presents a simplified approach, *U* and *L* are not explicitly modeled. Instead, the continuous plant is modeled by defining the limited processing capacity of the plant. When the plant is over capacity $(Q_{Tot} > U)$, the delivery truck waits to unload the concrete. When the plant is under capacity $(Q_{Tot} < L)$, the plant idles and the concrete pumping stops. When the plant is between the limits $(L \leq Q_{Tot} \leq U)$, the plant operates at the production capacity.

In this research, a modeling framework is proposed to build a "combined" model for a "continuous" processing plant interconnected with "discrete" truck arrivals to deliver and feed materials. The proposed modeling framework is illustrated by a concrete pump case. *SDESA* is used as the process mapping and simulation methodology to illustrate the application of the proposed framework.

Let us take the modeling of a concrete pump for example: at a building site, mixer trucks deliver concrete into the feeder of a stationary pump. Note in contrast with discrete resources commonly encountered and matched in construction (such as a truck, an excavator, and a crane), a buffer is the hallmark of a continuous plant (such as the unloading container); one or multiple feeder resources can be simultaneously processed subject to the production capacity of the plant. Concrete is continuously pumped up the pipeline from the unloading point to the placing point on the upper floor. In the development of a discrete simulation model of the entire site operations, one critical issue is how to represent the pump's production capacity in processing mixer trucks and placing concrete. An easy way to model the concreting process is to treat the pump as one scarce resource, which is then matched with one mixer truck before engaging in the pumping activity.

As shown in Figure 6.2, two "Queue" nodes plus one "Combi" activity form a basic *CYCLONE* model structure, with the "Pump Queue" and the "Mixer Truck Queue" denoting the resource requirements to invoke the pumping activity. One resource entity is initially placed in the "Pump Queue" (as symbolized with an asterisk) to indicate the availability of one pump resource at site.

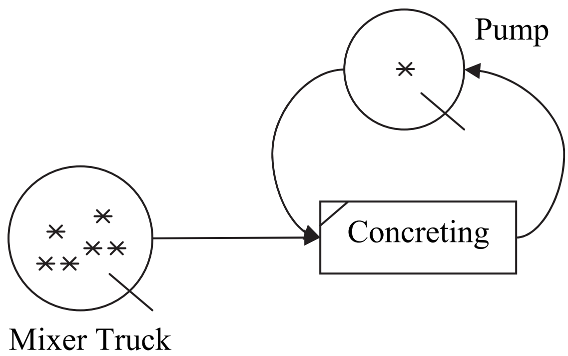


Figure 6.2. Simple *CYCLONE* Model for Concrete Pumping Process

The "Mixer Truck Queue" is initialized according to prescheduled truck delivery time (shown in Figure 6.2), or alternatively, is dynamically linked to the concrete delivery cycle between the batching plant and the building site. Note the quantity of concrete carried in one truck load is known; and the activity time distribution of "Pumping Combi" models the uncertainty in the processing time required for unloading concrete from one truck at the site. The above *CYCLONE* model structure is commonly used to represent conveyers in batching plants or pumps in building sites in previous research of concrete-placing operations simulation (e.g. Zayed and Halpin 2000). However, the continuous nature of the concrete pumping operation would likely render the discrete model in Figure 6.2 inaccurate, especially when the production capacity of the pump is high. This is explained as follows.

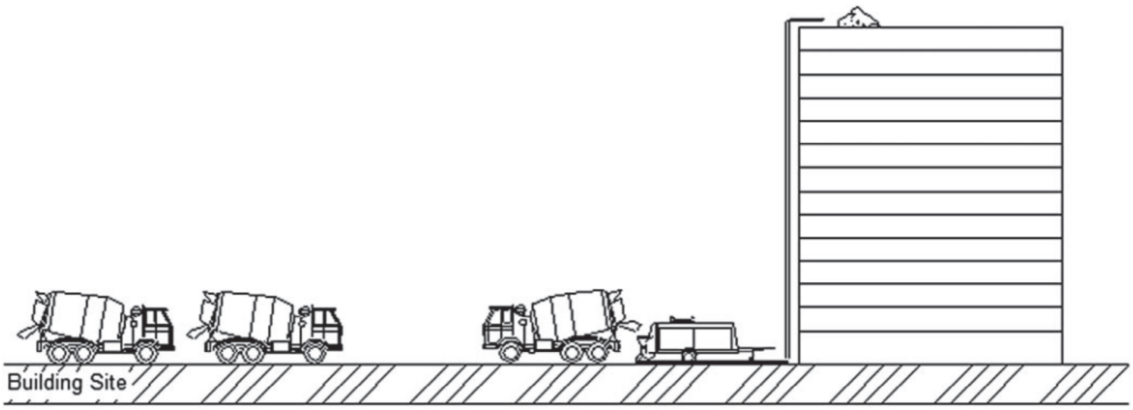


Figure 6.3. Illustration for Continuous Concrete Pumping Process

A stationary pump with a production capacity of 42 cum per hour is used for casting structural elements on the 20th floor in the building construction as shown in Figure 6.3. Mixer truck s of 7-cum volume capacity each arrive at the site in time, ensuring smooth, continuous concrete pumping. Given the average duration for unloading one 7-cum mixer truck is 20 min, the simulation result in the first one hour can be deduced by quick hand simulation based on the simple *CYCLONE* model as shown in Figure 6.2. From the start to the 20th minute, the first truck load is processed by the pump. From the 21st minute to the 40th minute, the second truck load is processed. Then, from the 41st minute to the 60th minute, the third truck load is processed. Over the first hour, the pump resource is 100% occupied and a total of 21 cum concrete is pumped. However, an obvious mismatch can be observed between the simulation result and the expected productivity performance with respect to the pump's production. The production rate of the pump is rated 42 cum per hour. That means with the pump running at its full capacity in the first hour, the actual quantity of concrete pumped is supposed to be close to six truck loads, i.e. 42 cum. Yet, executing the *CYCLONE* model would have only yielded three truck loads (or 21 cum.) In short, the above simple case has exposed a potential pitfall in the modeling of a continuous plant by applying discrete event simulation. As a matter of fact, the pump has the production capacity of unloading two mixer trucks simultaneously; how to model the pump by discrete event simulation is as follows.

To fix the problem, several parameters are designated: 1) the production rate of the continuous plant in terms of the quantity of material processed in an hour as *P*; 2) the event time of "start processing one unit of production (truck load)" as t_1 and the event time of "finish processing one unit of production" as t_2; and 3) the quantity of material delivered by one truck load as *q*. Here, Equation (1) is proposed to determine the quantity of "pseudo resource entities" *(N)*, used to initialize the availability of the continuous plant:

$$N = \frac{\int_{t_1}^{t_2} P \cdot dt}{q} = \frac{\overline{P} \times (t_2 - t_1)}{q} \qquad (1)$$

The following explanations of the definition of *N* are given:

- *N* is dimensionless and rounded off to the closest integer. Different from the quantity of discrete resources commonly used in construction (such as equipment, tools or crews), *N* is not the actual count of physical resource elements but the quantity of "pseudo resource entities" specifically defined to model the production capacity of a continuous plant; in this case, N = 2, but this does not mean two pumps are available in the jobsite; actually, only one pump is used.

- The numerator is the integration of the production rate *(P)* of the continuous plant over the time period $[t_1, t_2]$ of one delivery unit (truck); $\overline{P}$ is taken as the average production rate of the continuous plant over that period. On the denominator, q is the quantity of material contained in one production unit (truck load).

- As a production unit represents the amount of material contained in one truck load, given a plant that handles the continuous flow of production units, the quotient N can be visualized as the maximum number of channels within the plant that allow the production units to flow in parallel; but N does not imply the available space on-site that can accommodate multiple delivery units (trucks) simultaneously for unloading.

- N is approximated as a constant based on the average or most likely values of $\overline{P}$, t_2-t_1, and q. Variability in those parameters due to random variations or uncertain site factors can be conditioned into the statistical distribution of activity time, which is used for Monte Carlo sampling during simulation modeling.

For the above-mentioned concrete pump example, the production unit is one truck load of concrete; $\overline{P}$, t_1, t_2, and q are 42 cum per hour, 8:00 a.m., 8:20 a.m., and 7 cum, respectively. Thus, N is decided to be 2:

$$N = \frac{\overline{P} \times (t_2 - t_1)}{q} = \frac{42m^3/hr \times (8:20 - 8:00)\min/60}{7m^3} = 2$$

To update the *CYCLONE* model (Figure 6.2), two resource entities are placed initially at the queue node associated with the pump's availability as shown in Figure 6.4. Then, repeating hand simulation on the *CYCLONE* model would result in six truck loads (or about 42 cum) of concrete being processed and 100% utilization for the two pseudo resource entities in the first hour (denoting full utilization on the pump). In the event of activity interruption due to concrete supply problems or other site factors, the pump would not operate at its full capacity. For instance, tardy concrete deliveries would cause interruptions to the pumping process, thus reducing the utilization rate of the two pseudo resource entities to 70%. This would bring down the pump production in the first hour from 42 cum (six truck loads) to 28 cum (four truck loads).

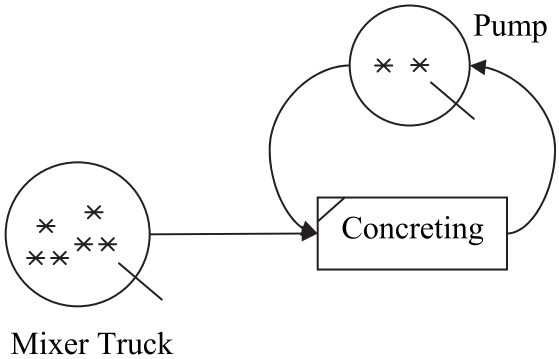


Figure 6.4. Updated *CYCLONE* Model with Two Resource Entities Being Placed Initially at the Queue Node Associated with the Stationary Pump

Next, practical applications of defining "pseudo resource entities" are presented to model 1) the production capacity of a continuous pump in concreting operations; and 2) the production capacity of a magnetic separation plant central to iron ore mining operations, which is based on the experience of utilizing discrete event simulation to facilitate optimizing equipment resource configurations for an iron ore mine situated in Indonesia.

6.6 Practical Applications

Two practical application cases are described: 1) modeling the production rate of a concrete pump; and 2) modeling the production capacity of a magnetic separation plant central to iron ore mining operations.

1) Modeling the Production Rate of a Concrete Pump

In concrete operations of a building site with a stationary pump fed by delivery trucks of 7-cum, the production rate of a concrete pump is modeled. The default hourly pumping rate of the stationary pump is 43 cum per hour. Twenty 7-cum delivery trucks is employed to the concreting process. The mean arrival time for the delivery trucks is scheduled 10 minutes. When a delivery truck arrives the site, a flagman will lead it to two designated parking areas depends their availability. Once the pump is not full, the delivery truck will unload 1 cum of concrete to the stationary pump until it is empty or the pump is full. The empty truck will leave the site with the assistance of a flagman when the unloading activity is completed. Maximum of two delivery trucks can unload at the same time. The activity durations are listed in Table 6.2.

Table 6.2. Activity Definitions for a Concreting Site

Activity	**Duration (min)**		
	Mean	**Low**	**High**
Park A	1	0.5	1.5
Park B	1	0.5	1.5
Pre-plant Process A	3	2.7	3.3
Pre-plant Process B	3	2.7	3.3
Plant Process	3	0.5	1.5
Post-plant Process	0.5	0.5	1.5
Leave A	1	0.5	1.5
Leave B	1	0.5	1.5

For the pre-plant processes refer to the unloading activity of the delivery trucks to the stationary pump, which takes 3 minutes per cum, i.e. with an unloading rate of 20 cum per hour. It takes 21 minutes to unload a 7-cum delivery truck. The production unit is one truck load of concrete, $\overline{P}$, t_1, t_2, and q are 43 cum per hour, 8:00 am, 8:20 am, and 7 cum, respectively. Thus, N is decided to be 2:

$$N = \frac{\overline{P} \times (t_2 - t_1)}{q} = \frac{43m^3 / hr \times 21\min/60}{7m^3} \approx 2$$

The resource pool for the concreting site is listed in Table 6.3. Note that the pseudo resource *(N)* is adopted as 2 for the *Plant*.

Table 6.3. Resource Pool for a Concreting Site

Resource Type	**Code**	**Amount**
Parking Area A	PARK_A	1
Parking Area B	PARK_B	1
Plant	PLANT	2
Flagman	FM	1
Parking Request	PARK_REQ	0
Raw Material A	RM_A	0
Raw Material B	RM_B	0
Work Material	WM	0
Plant Material	PM	0
Capacity	CAP	5
Leave_A	LEAVE_A	0
Leave_B	LEAVE_B	0

The total *SDESA* model is shown in Figure 6.5. The mean activity durations were applied for model validation purpose. The total time to process twenty truck load of 7 cum is 242 min. The actual hourly pump rate is equal to:

$$20 \times 7cum \div (242\min \times \frac{1hr}{60\min}) = 34.71 cum/hr$$

The utilization rate of pump can be determined as the actual hourly pump rate divided by the default hourly pump rate:

$$\frac{34.71}{43} \times 100\% = 80.72\%$$

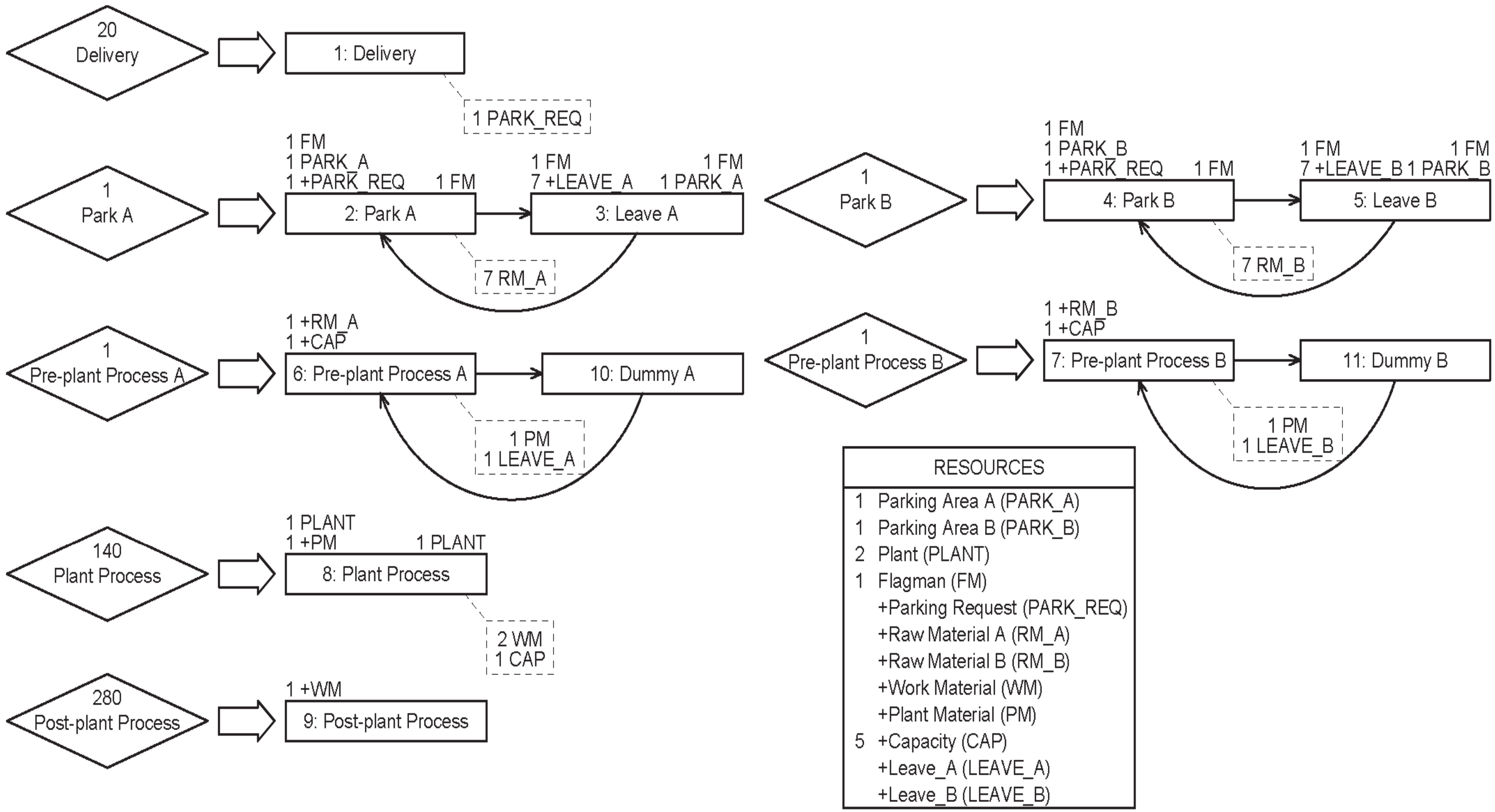


Figure 6.5. Total *SDESA* Model of a Concreting Site

From the results, the production rate of pump shows a good match with the truck unloading activity.

After the model is validated, 100 Monte Carlo simulation runs are carried out using the uniform distribution activity durations in the simulation model. The mean total time to process all pumping production is 242.46 min with Variance of 5.19 min. The actual hourly pump rate is equal to:

$$20 \times 7 cum \div (242.46 \min \times \frac{1 hr}{60 \min}) = 34.64 cum / hr$$

The utilization rate of pump can be determined as the actual hourly pump rate divided by the default hourly pump rate:

$$\frac{34.64}{43} \times 100\% = 80.57\%$$

From the results, the production rate of pump shows a good match with the truck unloading activity.

2) Modeling the Production Capacity of a Magnetic Separation Plant Central to Iron Ore Mining Operations

The production capacity of a magnetic separation plant in iron mining operations is modeled. The plant used in the actual site operations is shown in Figure 6.6. The raw sand flurry flows through a series of magnetic drums continuously. As output from the processing plant, the iron sand is separated from waste sand and stone.

Figure 6.6. Raw Material Slurry Undergoing Magnetic Separation

The production rate *(P)* of the magnetic iron sand separation plant is designed as 140 ton iron sand per hour. Each truck load carries 19 ton of raw material, 15% of which (4.12 ton) is iron sand, whereas the remaining 85% is waste. The production output of magnetic separation plant *(q)* in terms of iron sand is equal to 4.12 ton. Observed from the site, the time duration required for the processing plant to unload one truck load $(t_2\text{-}t_1)$ is observed to be 9 minutes on average. Thus, N is determined as:

$$N = \frac{\overline{P} \times (t_2 - t_1)}{q} = \frac{140 ton / hr \times 9 \min / 60}{4.12 ton} \approx 5$$

Hence, the magnetic separator plant can be modeled with five "pseudo resource entities" in a discrete simulation system. Chapter 6 gives a detailed complete simulation modeling and application for the mining project.

6.7 Discussion and Conclusions

In the construction domain, a plant of continuous nature often constitutes the leading resource in a site production system, which dictates the configuration of supporting resources and controls the overall productivity performance. The SLAM/AweSim system (Pritsker and O'Reilly 1999) is most commonly used for discrete-continuous combined simulation in construction research. Nonetheless, in spite of achievable modeling sophistication and accuracy, a combined simulation approach in general gives rise to additional time spent in developing the simulation model. Rather, construction modelers prefer a more convenient alternative to essentially "discretize" the modeling of continuous elements in a predominantly discrete system. As such, direct application of a discrete simulation method (such as *CYCLONE*) would afford the straightforward solution to the combined simulation problem.

This chapter has addressed the issue of how to model the production capacity of a continuous plant by using discrete event simulation. A plant of continuous nature relies on a material-handling mechanism (such as conveyer or pipeline) to continuously convey material delivered in truck loads to a designated activity location at the site. This research has exposed the potential loopholes in modeling a plant of continuous nature by oversimplifying it as one discrete resource entity, illustrated with a concrete pump example. An approximate method was formalized for representing a continuous plant with *N* discrete resource entities in simulation of a predominantly discrete operations system. *N* is the quantity of "pseudo resources" with no physical meaning, only representing the continuous plant would process *N* feeder resources simultaneously if the plant were modeled by *DES*, as such the passing capacity of the plant matches the simulation result. Two discrete simulation methods developed for modeling construction systems, namely, the well-established *CYCLONE* and the *SDESA*, were briefly described. The two simulation methods are used in a simple concrete pump example to illustrate how to model a construction plant of continuous nature by defining a certain number of discrete resource entities. A practical application was described to demonstrate the usefulness and flexibility of a discrete simulation methodology in modeling complicated construction systems. In conclusion, the proposed method adds to the usefulness and flexibility of a discrete simulation methodology in modeling complicated construction systems. The proposed simulation methodology reduces application time and cost in comparison with applying conventional combined modeling, which can be applied to any discrete simulation methods, not limited to *CYCLONE* or *SDESA*.

Chapter 7

Combined Modeling of the Mining Plant - Indonesia Case

7.1 Introduction

This chapter demonstrates the computer application of the proposed framework for process mapping model and the straightforward combined modeling method in order to cope with modeling a mining site, which is predominantly discrete but contains a processing plant that is continuous in nature.

The remainder of this chapter is organized as follow. The background of the case study is described in Chapter 7.2. The simulation objective is defined in Chapter 7.3. The computer application of the framework for process mapping model together with combined modeling of a processing plant is demonstrated in a mining project in Indonesia in Chapter 7.4. Model validation is discussed in Chapter 7.5. The discussions and conclusions are given in Chapter 7.6.

7.2 Background of Case Study

The mining case is characteristic of both a construction system and a manufacturing system. And the mining company initiated a trial run of 1.5% of the whole project to try out the plant, machines and crew size, and to optimize the configuration of major resources and processes. The trial run lasted for a year, preceding the 10-year span for the whole mining operation. Figure 7.1 shows the iron ore processing plant at the Indonesian mining site. Combined simulation modeling is first introduced in the context of the mining case.

Figure 7.1. Iron Ore Processing Plant at Mining Site in Indonesia

7.3 Simulation Objective

To improve cost-efficiency and competitiveness, the mining producer decided to explore a simulation approach to design effective site operations, aimed at maximizing the resource utilization rates and synchronizing the processing plant (magnetic separator) with various workflows. Thus, the trial runs on the prototype simulation models were performed before proceeding with the site operation on the actual full-scale system.

The most critical resource from the trial run was the processing plant of which the maximum production rate was the target production rate for the whole mine. Since the processing plant constituted a bottleneck in the system, the other processes in the whole iron ore production should be designed to be in line with the production capacity of the processing plant. One of the objectives for application of simulation modeling in the trial run was to determine the number of trucks for transportation between the ore digging area and the processing plant, and between the processing plant and the port, respectively. As the whole mining production was analogous to a production line, the formation of bottleneck in a sub-activity would subsequently reduce the production rate of successive processes. Not only would the whole production line fail to achieve the target production rate, but also the significant "waste" in operations would be generated in terms of plant cost, labor cost, diesel, and truck rentals.

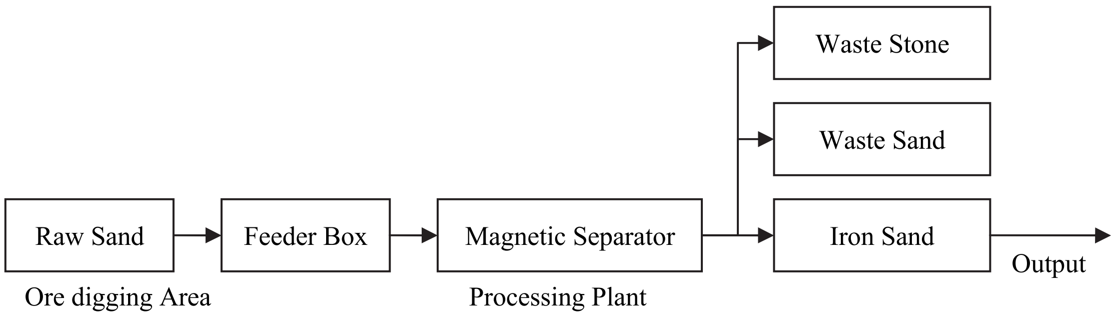
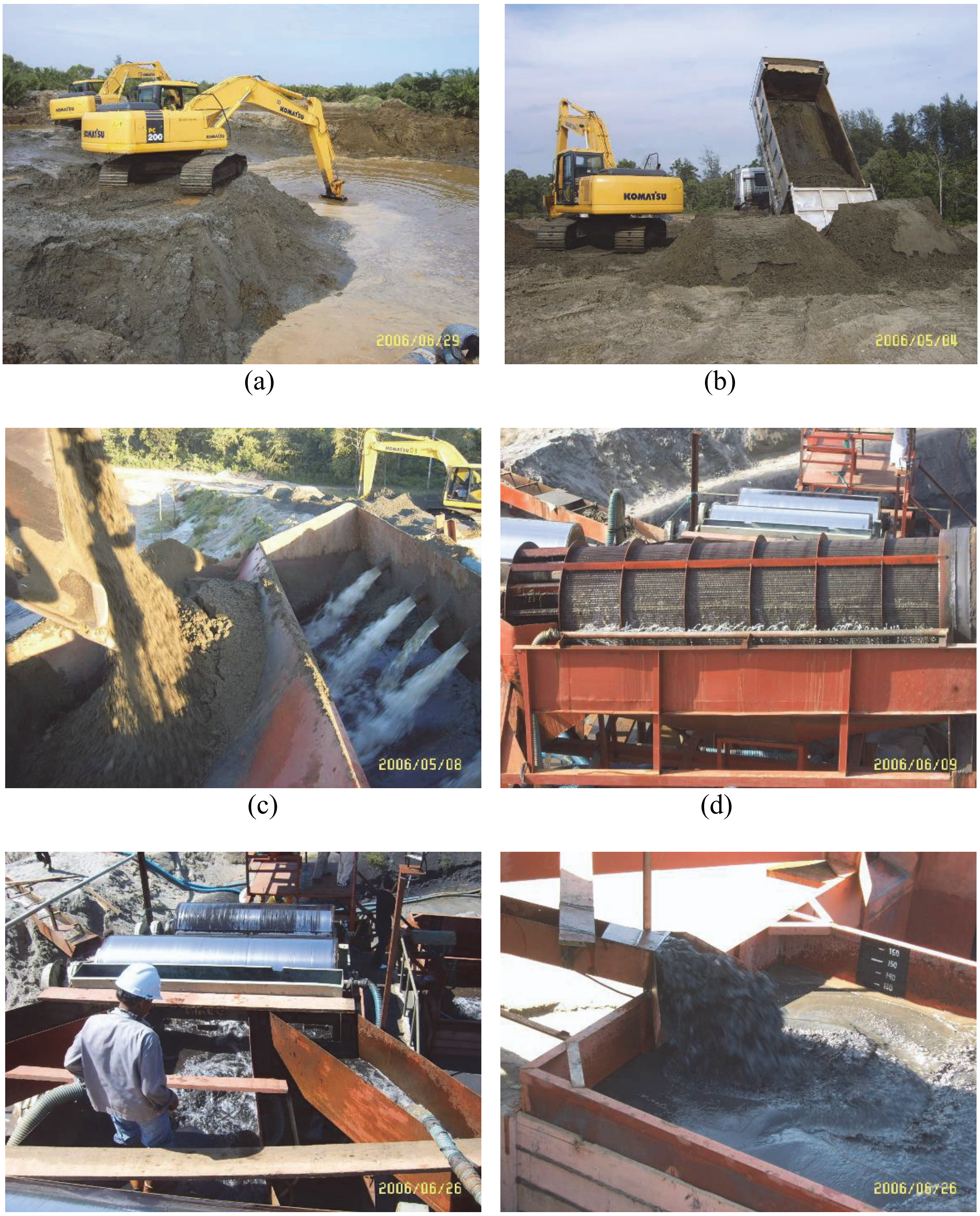


Figure 7.2. Schematic Flow of Iron Sand Processing

Figure 7.2 illustrates the schematic flow of the iron sand processing from raw sand into iron sand, stone, and waste. As shown in Figure 7.3, the raw sand at the ore digging area was excavated by excavators and transported to the processing plant by trucks. It was then unloaded near the magnetic separator plant, into a feeder box, screened, and separated by magnetic drums into iron sand, which eventually ended up flowing into the sedimentary tank. The waste stone and waste sand were produced as by-products and used for environmental-friendly embankment construction. The resulting iron sand was then transferred into the temporary drying box to dewater, followed by being transported to the site temporary storage. Trucks would be called in every four days to haul the dry iron sand to the port for storage. Upon the arrival of the barge, the iron sand would be loaded to it. Due to the shallow water depth, the barge was used for transportation between the port and the mother vessel by which the iron sand would be shipped to a destination steel mill.



(a) (b) (c) (d) (e) (f)

Figure 7.3. Site Photos of Mining Operations

Note: (a) Excavator digging raw iron sand; (b) Raw iron sand transported by truck and dumped near the magnetic separator plant; (c) Raw sand loaded into the feeder box of the processing plant; (d) Screening of raw sand; (e) Magnetic separator plant continuously extracting iron sand from the slurry of raw sand; (f) Iron sand flowed into sedimentation tank.

During the trial run, the overall target production rate of iron sand was set to be 50,000 ton per month (i.e. 140 ton per hour). The target production rates for four main production flows, namely, raw sand segregation; iron sand processing; stone processing; fine waste processing, were subsequently determined by factoring relative densities and material mix proportions.

The iron sand production resembles earth-moving operations in heavy construction and consists of five main processes: 1) the production of raw sand at the iron ore digging area, 2) the transportation of raw sand from the digging area to the processing plant by trucks (about 1 km travel distance), 3) the magnetic separation of raw sand into iron sand, waste stone, and waste sand by the processing plant, 4) the waste handling operations by loaders, and 5) the transportation of iron sand from the processing plant to the sea port by trucks (about 60 km away).

7.4 Computer Application of Process Mapping Model

In this case study, the processes yielding discrete batches of intermediate and final products were defined as discrete processes. Examples included the backhoes, which always picked and transferred intermediate products in buckets; and the trucks, which always transported intermediate products in truck loads.

In contrast, the processes, which produced products that could not be easily quantified in batches and yielded continuous product flows, were defined as continuous processes. Examples included the processes within the processing plant, such as the continuous running of well-mixed raw ore flows in the screening and magnetic separation, and the subsequent flows of the intermediate products in the channels of the magnetic separator plant. A detailed discussion on modeling the production capacity of a continuous plant is given in Chapter 6.2.

As shown in Figure 7.4, two types of work flows were used in the *SDESA* model. The first one was vehicle loop; ten trucks were used as the flow entity to model the transportation cycle between the raw iron ore and the processing plant. When the trucks were loaded with raw ore, they transported the raw ore to the feeder box and returned to the digging area for another cycle. The other one was production line in which the work unit was defined as a flow entity. The raw iron ore were washed and sifted by the processing plant in three stages: the preliminary screening through a feeder box, the magnetic separation, and the flow of iron sand though a channel leading to the collection box. As such, waste stones and waste sand were filtered out and different materials flowed through the channels to the designated locations for subsequent treatment.

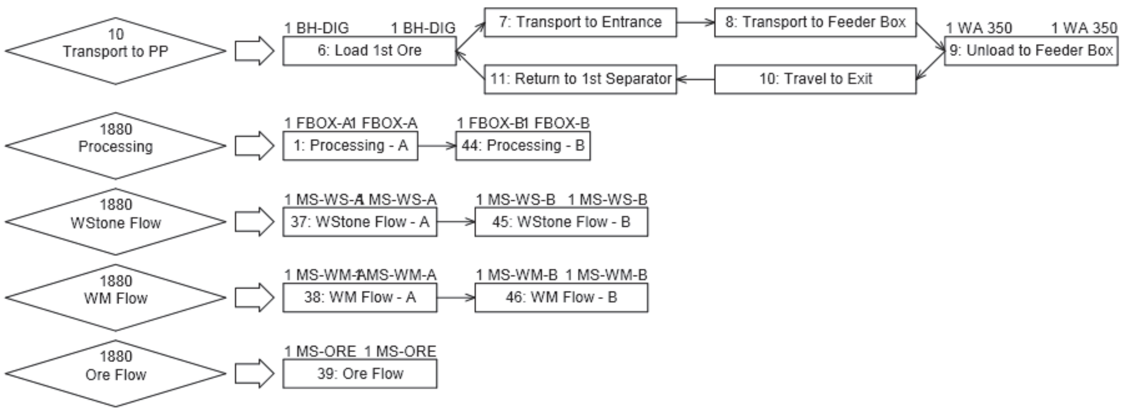


Figure 7.4. *SDESA* Model of Mining Process from Digging Area to Processing Plant

As shown in Figure 7.5, the full *SDESA* simulation model represents an aggregate of multiple workflows. Activities comprising each work flow along with activity times in the form of uniform distributions or constants are summarized in Table 7.1.

Table 7.1: Activity Definitions of Mining Project in Indonesia

Workflows	Activities	Mean Duration (min)
Transport to Processing Plant	Load 1st Ore	5
	Transport to Entrance	3
	Transport to Feeder Box	2.4
	Unload to Feeder Box	1.8
	Travel to Exit	1.8
	Return to Raw Ore	2
Processing	Processing	3.6
Waste Stone Flow	Waste Stone Flow	9
Waste Material Flow	Waste Material Flow	9
Ore Flow	Ore Flow	9
Transport to Temp Drying Box	Load 5th Ore	2
	Transport to Temp Drying Box	0.3
	Unload to Temp Drying Box	1
	Return to Product Output	0.2
Transport to Site Stockpile	Load 6th Ore	2
	Transport to Site Stockpile	0.5
	Unload to Site Stockpile	1
	Return to Temporary Drying Box	0.4
Transport to Port Stockpile	Load 7th Ore	2
	Transport to Exit	0.6
	Transport to Port Stockpile	156
	Unload to Port Stockpile	1
	Return to Entrance	130
	Return to Site Stockpile	0.5
Transport to Berth	Load 8th Ore	2
	Transport to Berth	0.6
	Unload to Berth	1
	Return to Port Stockpile	0.4
Transport to Mother Vessel	Load 9th Ore	0
	Transport to Berth	30
	Unload to Berth	10
	Return to Port Stockpile	20
Waste Stone Dumping	Load Waste Stone	2
	Transport Waste Stone to Waste Material Embankment	0.7
	Unload Waste Stone to Waste Material Embankment	0.8
	Return to Waste Stone Storage	0.6
Waste Material Dumping	Load Waste Material	2
	Transport Waste Material to Waste Material Embankment	0.7
	Unload Waste Material to Waste Material Embankment	0.8
	Return to Waste Material Storage	0.6
Embankment Construction	Embankment Construction	4

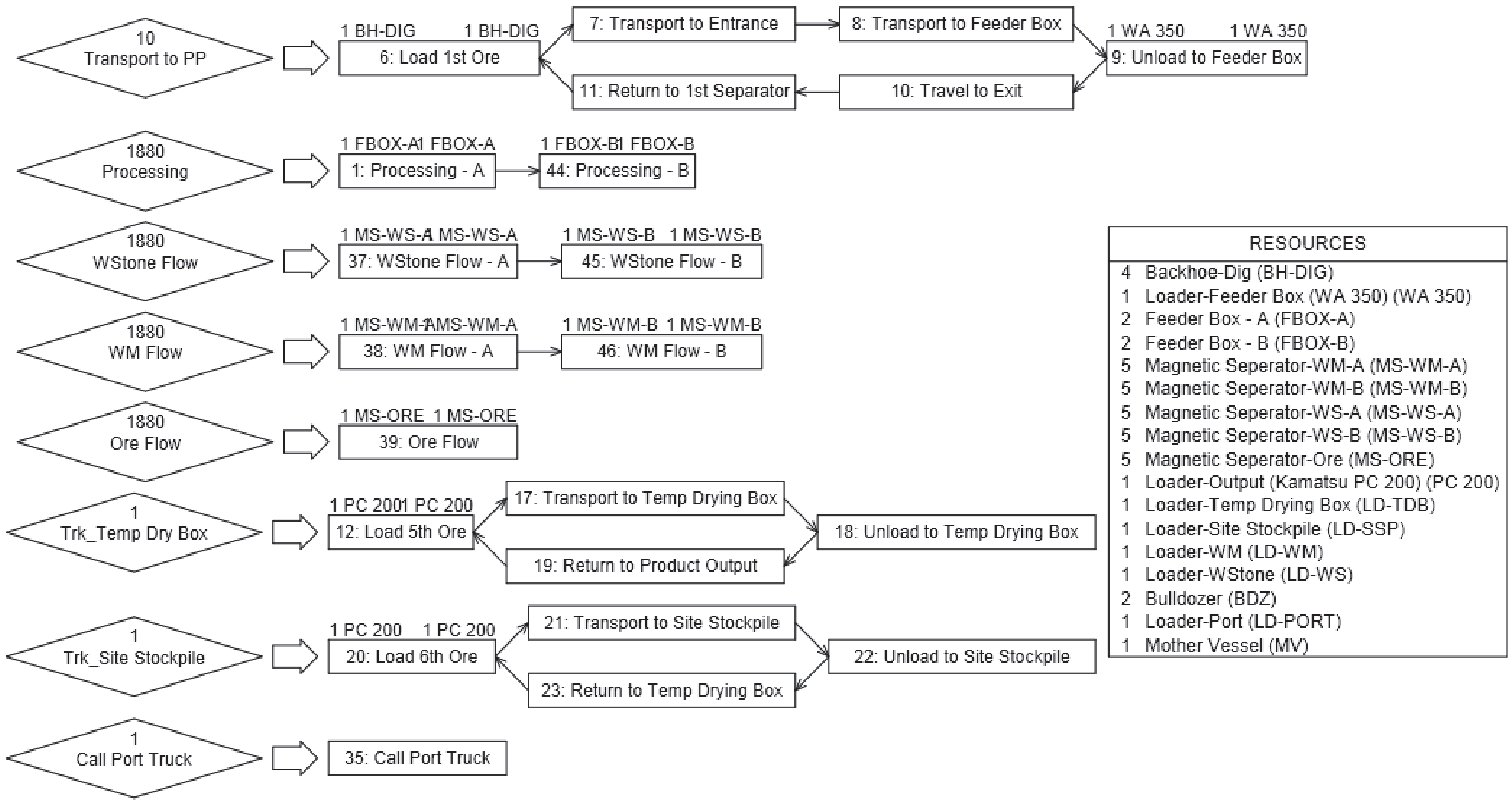


Figure 7.5. Total Model of Mining Project in Indonesia in *SDESA*

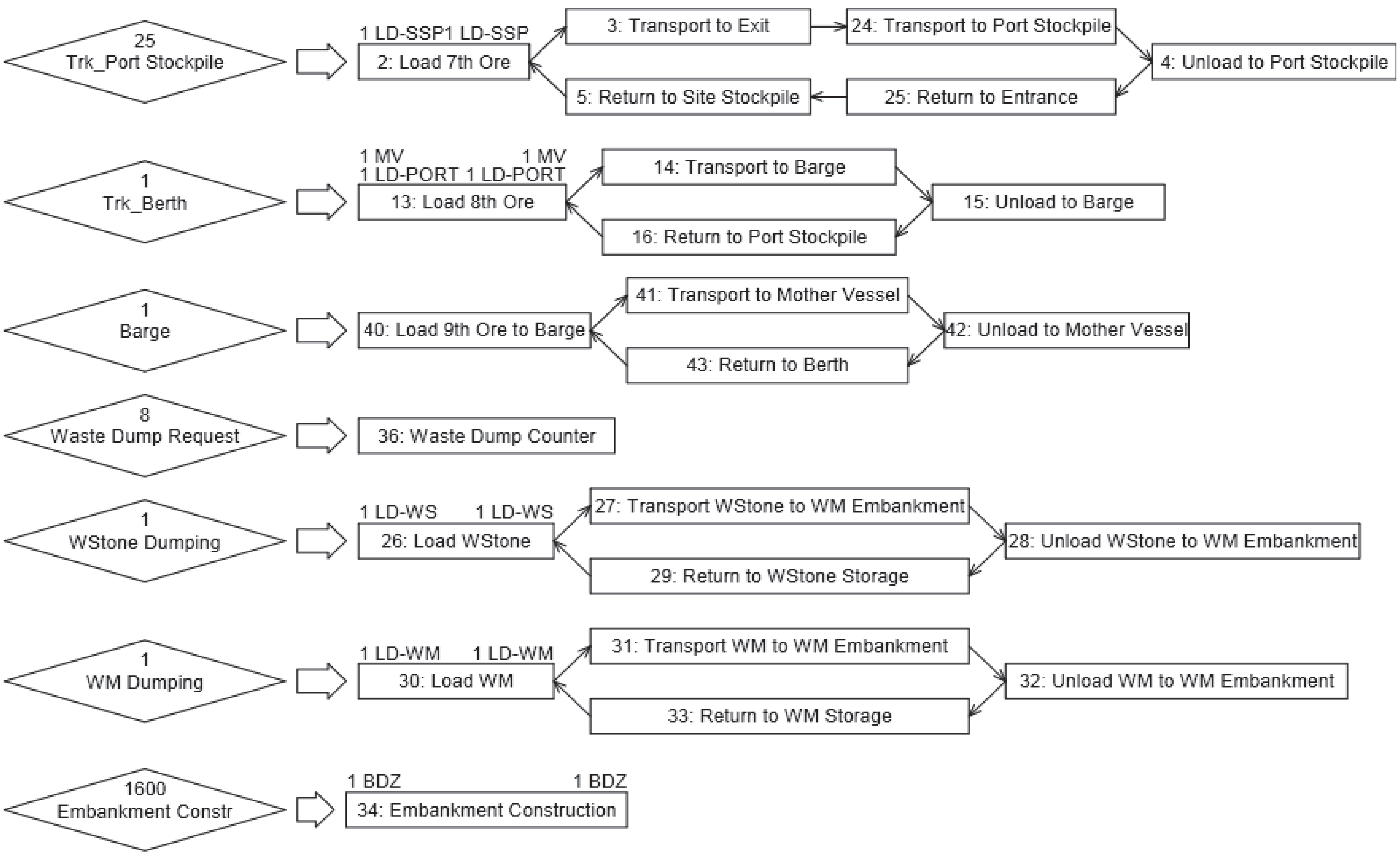


Figure 7.5. Total Model of Mining Project in Indonesia in *SDESA* (con't)

For this production line, the "pseudo resource entities" (N) were defined to simulate the continuous nature of the operations in the processing plant. N is a dimensionless integer, the quantity of which represents the production capacity of the continuous process plant. Unlike common construction resources, N does not represent the actual amount of the resource. N is defined mathematically in Equation (1):

$$N = \frac{\int_{t_1}^{t_2} P dt}{q} = \frac{P \times (t_2 - t_1)}{q} \quad (1)$$

Where P is the production rate of the production plant; t_1 is the start time of an activity; t_2 is the end time of an activity; q is the quantity of material contained in a discrete batch. The numerator is the integration of the production rate of the continuous plant over the time period (t_2-t_1). The difference of (t_2-t_1) can be taken as the average time duration for processing one production unit, but it is notable that during this time period, more than one production unit can be processed in parallel. On the denominator, q is the quantity of material in one production unit (truck load).

Simulation experiments were conducted on the *SDESA* simulation platform so as to find the proper resource configuration of the system that would best match up with the processing plant. The modeling of the magnetic separator plant is shown in Figure 7.6.

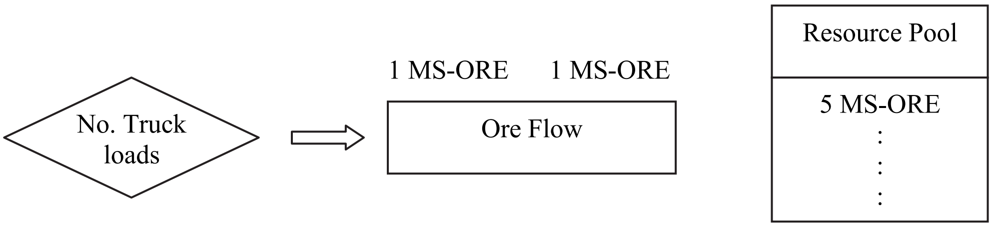


Figure 7.6. Modeling of the Magnetic Separator Plant in *SDESA*

In the *SDESA* model, "1 MS-ORE" is marked on the upper-left corner of the activity block of "Ore Flow" to denote one available MS-ORE (magnetic separator) resource entity is required for processing one truck load of raw material; on the other hand, the "1 MS-ORE" on the upper-right corner of the activity block indicates that the MS-ORE resource entity is released at the end of the activity. The number of truck loads to be processed is initialized in a flow entity diamond linked to the "Ore Flow" activity. Note five "pseudo resource entities" ("5 MS-ORE") are initialized in the resource pool of the *SDESA* model in order to accurately represent the continuous iron sand magnetic separation process.

The iron sand production over time resulting from simulation is shown in Figure 7.7. Note the initial 25 minutes section in Figure 7.7 is the warm-up period, during which the first truck load of raw sand is prepared and transported.

The magnetic separation plant used in mining operations is identified as a continuous plant. The production rate (P) of the magnetic iron sand separation plant is rated as 140 ton iron sand per hour. Each truck load carries 19 ton of raw material, 15% of which (4.12 ton) is iron sand, whereas the remaining 85% is waste. The production output of magnetic separation plant *(q)* in terms of iron sand is equal to 4.12 ton. Observed from the site, the time duration required for the processing plant to unload one truck load (t_2-t_1) is observed to be 9 min on average. Thus, N is determined by Eq. (1).

$$N = \frac{\int_{t_1}^{t_2} P \cdot dt}{q} = \frac{\overline{P} \times (t_2 - t_1)}{q} = \frac{140 ton/hr \times 9 \min/60}{4.12 ton} \approx 5$$

Hence, the magnetic separation plant can be modeled with five "pseudo resource entities" in a discrete simulation system.

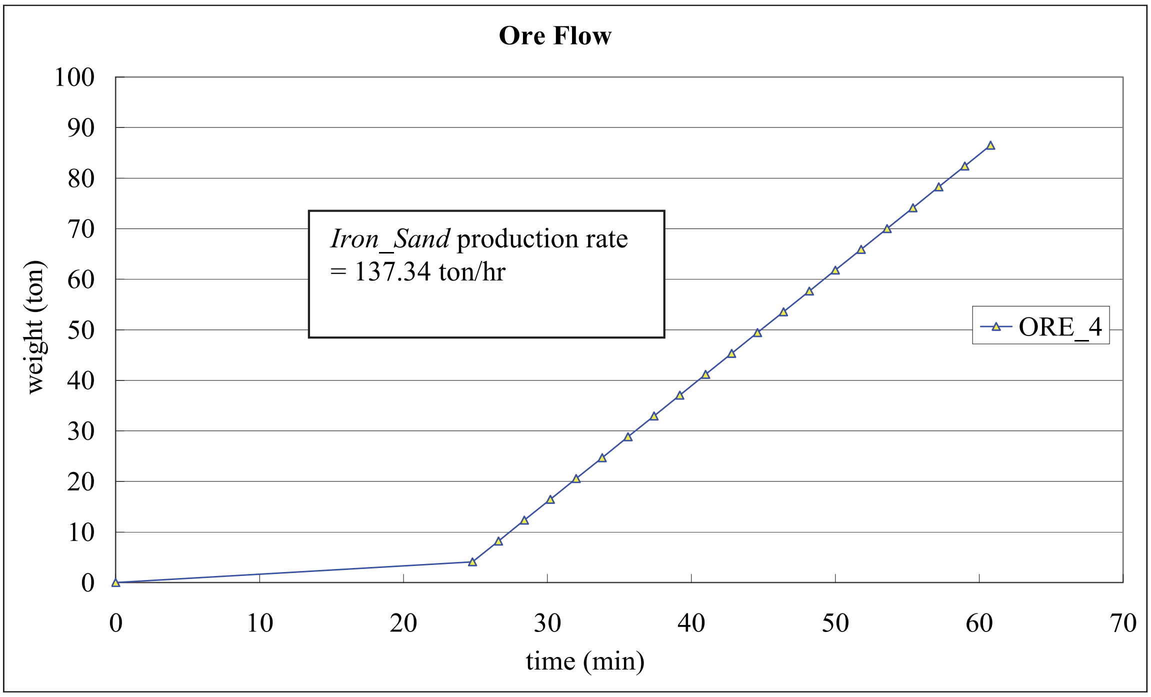


Figure 7.7. Iron Sand Production over Time Resulting from *SDESA* Simulation

$$\text{Iron sand production rate } (P_{Iron\_Sand}) = \frac{86.52 - 4.12}{60.8 - 24.8} = 2.289 \text{ ton/min}$$

$$= 2.289 \text{ ton/min} \times \frac{60 \text{ min}}{1 \text{ hour}}$$

$$= 137.34 \text{ ton/hr}$$

In order to attain continuous operation of the magnetic separator processing plant at its full capacity, the following was discovered through simulation experiments: 1) four backhoe excavators should be made available at the digging area for raw sand excavation; 2) ten trucks (each having a payload of 19 tons) should be used for moving the raw sand from the digging area to the processing plant (about 1 km travel distance); and 3) twenty-five trucks (each having a payload of 19 tons) were required to transport the iron sand as produced from the processing plant to the port (about 60 km away).

The simulated production rate of the magnetic separation processing plant is 137.34 ton/hr, which is close to the rated capacity of the plant (140 ton/hr). The simulation results served as valuable input to design the iron ore production system and provided analytical evidence for the mining company to streamline its truck fleet, giving rise to considerable cost savings in terms of truck rental and fuel cost.

The model result regarding the warm-up period is shown in Figure 7.8. From the *AO3* (separated ore) curve, the first 4.12 tons of ore had been separated at 15.8 min while *Ore_4* (iron ore dropped into the sedimentation tank) was yielded at 24.8 min. The simulation-derived production rates for different intermediate products (also referred to as the production rates for the magnetic separator and the flow channel) are calculated as follows.

According to in Figure 7.8, the ore separation rate can be determined from the *AO3* production rate (P_{AO3}): $\frac{(107.12-4.12)ton}{(60.8-15.8)\min} \times 60\text{min/hr} = 137.3$ ton/hr

Warm-up period = 15.8min

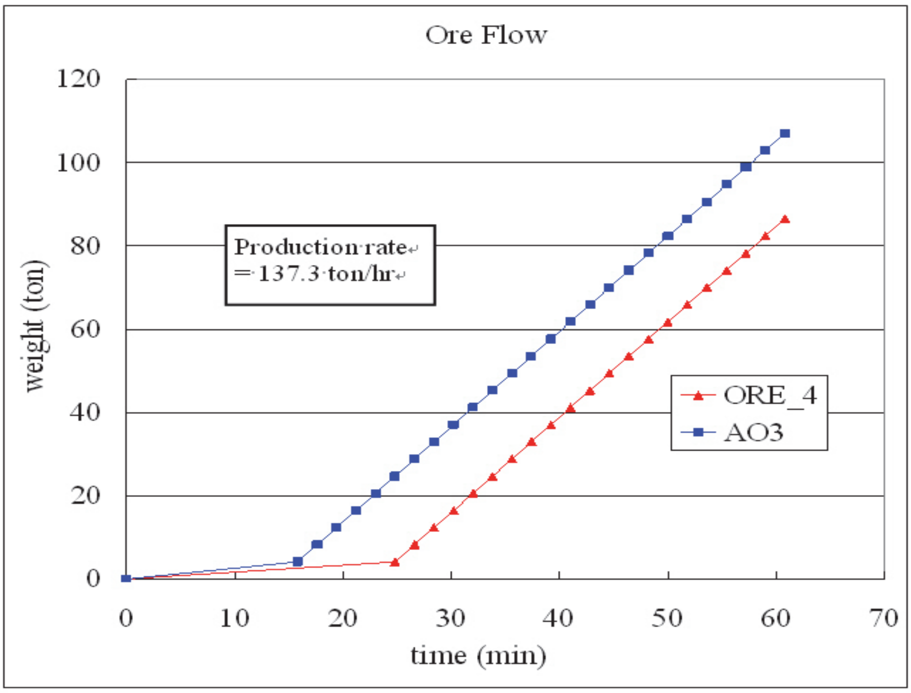


Figure 7.8. Ore Production over Time Resulting from *SDESA* Simulation

Similarly, the ore flow rate from channel into the sedimentary tank is determined from the curve *Ore_4* in Figure 7.8.

Iron Sand production rate (P_{Iron_Sand}) = $\frac{(86.52-4.12)ton}{(60.8-24.8)\min}$ x 60min/hr = 137.3 ton/hr

Warm-up period = 24.8min

Utilization rates of the resources

Through simulation experiments, the resource provisions to the mining system were configured and the utilization rates of the resources obtained from *SDESA* simulation are summarized in Table 7.2.

Table 7.2. Utilization Rates of the Resources in Mining Project in Indonesia

Resource	Quantity	Utilization Rate (%)
Backhoe-Dig	4	69.5
Truck transport to processing plant	10	88.7
Loader-Feeder Box (WA350)	1	99.7
Feeder Box	1	99.6
Magnetic Separator	1	99.4
Truck transport to temporary dry box	1	29.0
Loader-temporary dry box (PC200)	1	33.4
Truck transport to site stockpile	1	32.6
Truck transport to port stockpile	25	99.9
Truck transport to berth	1	16.6
Loader-Waste Material	1	47.7
Loader-Waste Stone	1	47.7
Bulldozer	1	95.2

From the result, the numbers of backhoes and trucks were deemed optimum while the loaders at the feeder box, feeder box and magnetic separator (MS) achieved their full capacity.

7.5 Model Validation

The model was set up based on the site manager's observation. The simulation output can be observed through animation as shown in Figure 7.9. The simulation results showed a close match between the model and the site production. The target production rate of 50,000 ton per month (140 ton per hour) was reached for the trial production period. The critical resource was the processing plant (feeder box and magnetic separator) from both the model and the site observation. Particularly, the model was instrumental in advising the mine manager: 1) four backhoe excavators should be made available at the digging area for raw sand excavation; 2) ten trucks (each having a payload of 19 ton) should be used for moving the raw sand from the digging area to the processing plant (about 1 km travel distance); and 3) twenty-five trucks (each having payload of 19 ton) were required to transport the iron sand as produced from the processing plant to the port (about 60 km away). The simulation results served as valuable input to design the iron ore production system; in particular, the simulation has provided analytical evidence to help the mining company streamline the truck fleet, bringing in considerable cost savings in terms of rental and fuel cost.

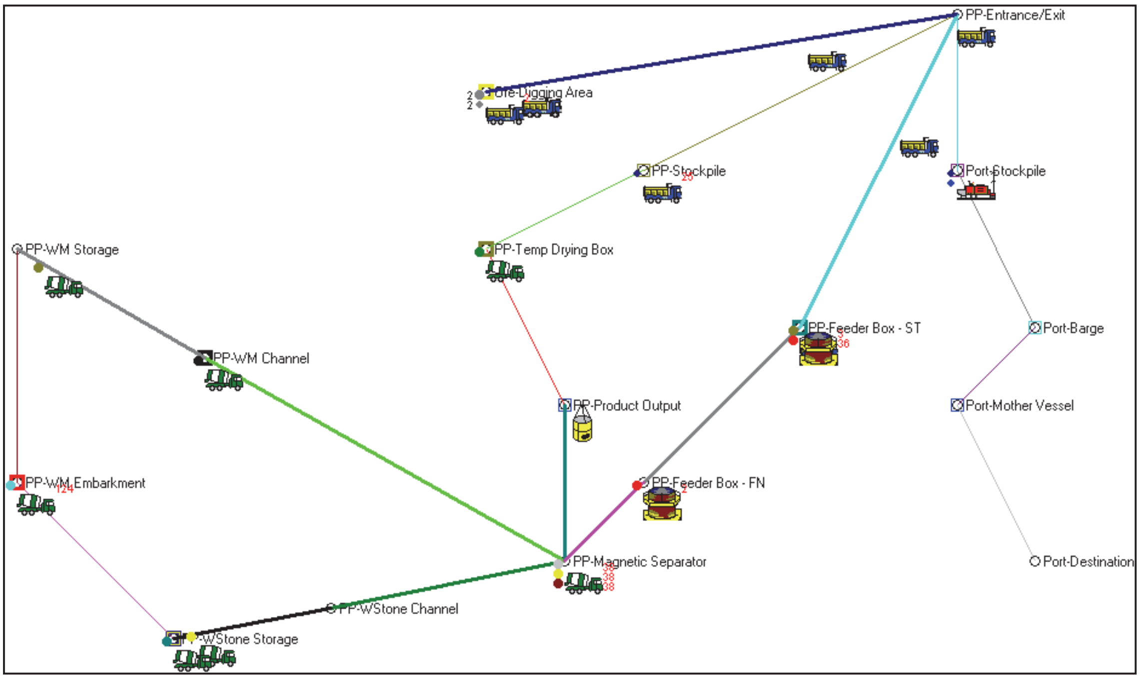


Figure 7.9. Screenshot of Animation View of the Total Model in *SDESA*

7.6 Discussion and Conclusions

In the construction domain, a plant of continuous nature often constitutes the leading resource in a site production system, driving the configuration of supporting resources and controlling the overall productivity performance. The *SLAM/AweSim* system (Pritsker and O'Reilly 1999) is the most commonly used for discrete-continuous combined simulation in construction research. Nonetheless, in spite of enhancements to project planning in sophistication and accuracy, a combined simulation approach in general comes at the expense of additional time spent developing a detailed model. Rather, construction modelers prefer a more convenient alternative to simulating the production capacity of the continuous plant, which essentially "discretizes" the modeling of continuous elements in a predominantly discrete system without loss of significance or accuracy. As such, a direct application of a discrete simulation method (such as *CYCLONE*) would afford the straightforward modeling solution to the whole site system.

An approximate method is formalized for representing a continuous plant by *N* discrete resource entities so as to ensure the accuracy of the model as desired while retaining the ease of applying discrete simulation modeling. This would not only enhance the usefulness and flexibility of the discrete simulation methodology in addressing complicated, real world construction systems, but also help reduce the application cost of construction simulation methods in terms of software expenses and learning efforts. Of course, the modeling focus is set on the resource availability and production capacity of a continuous plant in a predominantly discrete operations system, where other continuous state variables do not constitute system constraints and hence can be ignored in simulation. A case of modeling iron ore processing in an Indonesian mine further demonstrates the application of the technique being proposed in the practical context.

Mining requires trial runs on a test scale to examine: 1) both the site operation including production line schematic design and resource allocation and 2) the quantity and quality of the mine ore and the sub-products (waste sand in our case). Preliminary design and adjustment of the production line on a small scale of the whole project provide valuable information to the mine operator so as to maximize cost-efficiency and profits. Simulation provides an effective means to support the managerial decision making and resource allocation. In this research, a case study is presented with simulation modeling application to justify the site resource configuration in engineering an open-pit iron mine in Indonesia. The input parameters and mining process information were sourced from the mine operator.

To allow for an effective representation of the continuous elements in a predominantly discrete system, the “pseudo resource entity” is defined to enable the continuous modeling within a simplified discrete-event simulation system (*SDESA*). The simulation results were compared with the site records, indicating good fits with regard to the production rate and resource utilization rate.

This chapter demonstrates the computer application of the framework for process mapping model with combined modeling of a processing plant in a mining site in Indonesia. The proposed simulation methodology reduces the application time and cost in applying conventional combined modeling. The model template lays a solid basis for further investigation of the mining operation on the full-run scale. An approximate method has been formalized for representing a continuous plant with *N* discrete resource entities in simulation of a predominantly discrete operations system, so as to ensure the accuracy of the model while retaining the ease of simulation modeling. The identified problem pertains to typical construction process (e.g. concrete pumping) or a typical process (e.g. mining process), and the proposed solution applies to any discrete simulation method (*CYCLONE*, *CYCLONE*-related, or any other discrete modeling tools).

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

The formalization of pseudo resource entities for representing a continuous plant in a construction/mining system is intended to serve the need of improving common construction resource utilization (trucks) and enhance operations productivity and logistical efficiency. The formalization is based on deep, extended research in construction operations and logistics simulation. It has been generalized in a way to benefit complicated applications. As given in the practical application of the thesis, a mining case study in the real world is used to demonstrate the merit of such formalization. The formalized approach has been conducive to the rapid development of a large iron ore mining model that facilitated critical decision making in reality.

Nonetheless, the application scope of the formalization is constrained to the predominantly discrete simulation applications reported in the literature. The resource undersupply glitch in modelling a continuous plant by discrete simulation is one "fatal" pitfall, as this would easily skew the production rate of a bottleneck resource/process, thus nullifying the validity of the whole system simulation. The formalization indeed is instrumental in avoiding inaccurate representation of the production capacity of a continuous plant in applying discrete event simulation. Two important issues associated with the use of discrete simulation to approximate a continuous process must be pointed out as follows:

First, the continuity in material handling flow is indicated by 100% combined utilization of pseudo resources of the plant in discrete event simulation. Suppose the pseudo resources are precisely determined to model the concrete pump. When tardy concrete truck arrivals occur, this would decrease resource utilization and production output while interrupting the continuous pumping operation. In fact, a valid simulation model serves well to schedule the arrival times of trucks thus guaranteeing the continuous pumping process. By common practice, scheduling just-in-time arrival of the next truck as the previous truck finishes pumping can be considered risky due to the uncertain factors in traffic. It is advisable to allow for a reasonable buffer (a queuing length of one or two trucks on site) in concrete logistical planning simulation in connection with a concrete pump (i.e. a continuous plant.)

Second, the loss of computing efficiency occurs if there is a real need to model discrete batches of material in minute details. Take concrete pumping for example: if it is really needed to model the flow of concrete through the pipeline in the pump with realistic granularity for a meaningful purpose (e.g. fluid dynamics design), one unit of concrete of 1 liter (1/1000 m^3) would be taken instead of 7 m^3 (truckload), then, this would result in too large a quantity of discrete entities flowing through the simulation model; as such, defining and tracking the precedence relationships among all the small batches of concrete while maintaining material flow continuity would become computationally inefficient. For the present research, the purpose is to improve construction field productivity instead of fluid dynamics design of the stationary pump. Hence, the use of a truckload as the basic discrete unit to flow through the simulation system is both sufficient and efficient.

It was intended to demonstrate the usefulness of the proposed framework through the applications to large civil engineering projects commonly encountered in real world. The current research focus is on developing the modelling methodology and making it work in addressing real world challenges. In addition, the validations in case studies in the present research have focused on the examination on flexibility and usefulness of the developed approach. Those cases are all on-going operations from realistic and complicated projects, reflecting the site-specific constraints. A close match between actual operations and simulation models in those cases is not easy to achieve by use of any established simulation method (such as *CYCLONE*) in a short time period.

For the magnetic separation in the iron ore plant, it is new to apply discrete event simulation to simulate the operation by continuous modeling through discretizing the continuous plant and processes. For airport case, the selective demolition was adopted and the waste management was regarded as one of the few pilot sites in Hong Kong that applied this approach to increase the recycling rate and minimize the waste. The simulation modeling has aided in planning for the field operations and benchmarked the selective demolition processes as the industry's best practice in waste management. A construction system lends itself well to discrete event simulation. As problems in the real world become larger in scale, more likely, a construction modeler needs to cope with a system that is predominately discrete but contains certain critical components that are continuous in nature, resulting in the need of performing "combined" modeling. Nonetheless, complexities inherent and the expertise required in applying combined simulation modeling would hamper its use by practitioners to improve their day-by-day work practices. In spite of potential enhancements to project planning in sophistication and accuracy, applications of combined simulation in the construction research literature are rare and cases of implementing combined modeling to lend construction managers with quantitative decision support are almost unheard of. In addition, the absence of sufficient detailed data as needed to cater for simulation modeling presents another major hurdle preventing the use of combined simulations.

In short, given an ideal scenario where modeling expertise and sufficient data are available, a combined modeling approach provides the effective simulation methodology to tackle the simulation of a complicated system and deliver valid solutions to aid the human modeler in making critical decisions. Unfortunately, the ideal scenario is rarely found in the real world of construction. The present research has exposed the potential loopholes in modeling a plant of continuous nature by oversimplifying it as one discrete resource entity, as illustrated with a concrete pump example. Moreover, an approximate method is formalized for representing a continuous plant by a finite quantity of discrete resource entities so as to ensure the accuracy of the model as desired while retaining the ease of applying discrete simulation modeling. This not only enhances the usefulness and flexibility of the discrete simulation methodology, but also helps reduce the application cost in terms of simulation software expenses and learning efforts.

Generalization from the results of the work to a reasonable higher level of complication of construction system could be relevant follow-up research topic in the future. The simulation models were developed following the proposed framework on an individual-case basis. For any similar projects, the basic model can be borrowed as the template and critically reviewed to suit different site conditions and constraints. When sufficient applications to numerous projects are established, generalization of that particular type of construction activities would be possible. In the future, it is also anticipated there would be more applications of formalized methodologies through this research in commercial capacity, whereas consulting business can be run using research deliverables.

8.2 Research Contributions

This research has developed a formal framework of process mapping and simulation approach to simulate large civil engineering projects. The proposed framework provides necessary guidance to approach, structure and represent large real world problems into simulation-friendly *process mapping models*. The process mapping models established are directly convertible into a simulation model by adopting the *SDESA* simulation modeling platform. In order to widen the application scope of the simulation, continuous plants and processes in large civil engineering projects which is predominantly discrete in nature are discretized as discrete resource entities. A finite quantity of the discrete resource entities were defined to represent a continuous plant or process so that it can be readily integrated into the discrete event simulation model without loss of model accuracy.

8.2.1 Academic Contributions

The academic contributions of the research include the formal framework for process mapping and simulation modeling, and a combined modeling approach generalized to simulate continuous components and processes accurately in discrete event system. The framework can formalize how to model large civil engineering projects found in real world, without making subjective interpretations and assumptions. The framework application results in a systematic flow chart, which provides detailed guidance for simulation modelers to develop process mapping models. Given the same problem, by eliminating unnecessary personal interpretations and assumptions, the simulation modeling structures themselves together with the simulation results obtained by various simulation modelers would agree with one another. The process mapping model, which is situated between real world applications and computer simulation models, provides a critical linkage to bridge the gap between real world applications and computer simulation solutions. Since the process mapping model is understandable by both simulation modelers and construction managers, more knowledge transfer is expected and more research undertakings can be collaborated. Moreover, the resulting process mapping model is readily convertible into a simulation model using the *SDESA* simulation modeling platform and forms the basis for further simulation analysis to be carried out. In addition, with the proposed approach to discretize a continuous plant as a finite quantity of discrete resource entities *(N)*, the construction processes that are predominately discrete in nature but contain limited continuous plants or processes can be readily handled with the discrete event system without considerable loss of model accuracy. The research deliverables have also been incorporated into teaching both undergraduate and graduate students in Construction Engineering and Management at University of Alberta by Dr. Ming Lu.

8.2.2 Industrial Contributions

The formalized framework for process mapping and simulation approach provides a critical linkage to bridge the gap between real world applications and computer simulation models. The resulting process mapping model acts as an effective communication tool between construction managers and simulation modelers. The formalized framework can be applied to virtually all the construction applications. The framework can formalize the way to model large civil engineering projects found in the real world.

Collaboration with experienced industry partners, who were also managers in charge of the two case projects (mining and pipe-jacking projects) respectively, two conference proceedings were produced through close liaison throughout model establishment and scenario analyses. Both provided positive feedbacks to the proposed simulation approach which can significantly benefit the project planning and operation. In addition, the simulation modelling approach was taught to a bachelor student, Mr. Lai Kar Shue, who was an experienced Works Supervisor under my supervision to develop a simulation application of a pipe-jacking construction site. It was also taught to a Residential Engineer, Mr. Hong Yee Wai, Tom, for establishing a simulation model of soil nail construction site. The research value in terms of providing critical decision support to professionals was examined and proven in various construction simulation applications.

8.3 Applications and Validation

The formal framework for construction simulation approach and the process mapping model were applied to three large civil engineering projects of 1) airport demolition, 2) microtunneling, and 3) mining. The framework is capable of solving a wide range of construction applications and the resulting process mapping models were converted to simulation models on the SDESA computer platform where the simulation analyses were carried out.

In the Kai Tai Airport demolition project, computer simulation revealed that the site operation was smooth and efficient with utilization rates of different types of resources ranging from 79 to 99%. The production rate derived from simulation indicated a close match between the simulation model and the actual site system. The resulting simulation model provided a basis for evaluating the cost efficiency of actual site operations and assessing alternative resource provision scenarios being postulated. By comparing the cost-time reduction ratios for four alternatives of resource provisions with the original base case, it was found that provided the project budget had satisfied the higher cash flow requirement, doubling the resource provision on site would potentially cut the project duration by half while not increasing the total direct cost.

For the So Kwun Wat microtunneling project, the research takes advantage of a twin tunnel construction as a unique "test bed" to implement operations simulation modeling with a view to improving the efficiency of microtunneling site operations and logistics. The first tunnel drive was taken as a "pre-drill" run in order to collect microtunneling cycle time data and soil data, map the main working processes being applied on site, and identify the practical constraints imposed on the site operations and logistics. The delays and interruptions to the operations encountered in the first tunnel drive were taken into account as the potential risks in planning for the second tunnel drive in building up the simulation model. Simulation results showed that the mean duration for drive through a 220-metre-long tunnel using the micro TBM is 52 days with standard derivation of 2.3 days. The utilization rates of the jacking system and facilitating resources vary from 89.3% to 96.5%. The simulation results showed a good match with the actual site performances.

In the mining project in Indonesia, the combined modeling approach was applied to simulate the continuous processing plants and processes in a discrete event system. The simulation results were compared with the site records, indicating a good fit with regard to production rates and resource utilization rates. The target production rate of 50,000 ton per month (140 ton per hour) was reached for the trial production period. The critical resource was the processing plant (feeder box and magnetic separator), which was identified from both the model and the site observation. The simulation results provided valuable insights to designing the iron ore production system; in particular, the simulation had provided analytical backup to help the mining company streamline the truck fleet, resulting in significant cost savings in rental and fuel. The proposed simulation methodology reduces both application time and cost in comparison with applying conventional combined modeling.

To conclude, computer simulation modeling and analysis based on the formalized framework for process mapping model was established and validated in those three real world applications. The proposed new methodologies are proven to be cost-effective means for supporting critical decision making processes during construction planning in terms of cost, time and resource management. Different simulation analyses can then be carried out to solve many engineering problems in project planning and operation stages including the cost efficiency of construction waste handling, microtunneling logistics and operations planning, and mining productivity analysis. The continuous mining process was handled with the newly generalized modeling method. By discretizing the continuous mining processing plant, the discrete event system represented the mining site effectively and formed a valid basis for ensuing simulation analysis.

8.4 Recommendations for Future Research

This research has 1) developed a formal framework for process mapping and simulation modeling in order to model large civil engineering projects, and 2) formalized a combined modeling approach to simulate continuous components and processes in discrete event system. Combining these two new methods, the research can be applied to virtually all the construction applications. As the industries in connection with the selected applications in this research were much different in nature, conclusions were drawn based on a close match found between simulation model outcome and actual site production in different cases, and how the simulation applications advise the managers for resource, cost and time management. Simulation results serve as valuable input to design the construction system; in particular, the simulation has provided analytical backup to help the industry partners involved to fully utilize the critical resources, streamline the truck fleet, bringing in cost savings in rental and fuel. It is very difficult, if not impossible, for synergizing those results from industries with so many fundamental differences. This can be a research direction in the future. Future research is suggested to take the step forward in extending the proposed framework of process mapping model. Two subject areas specific to the construction engineering applications being studied have been identified for extending this research.

First, temporary traffic management for the microtunneling site was identified critical through observation during visits to different sites and discussion with construction managers. In well-developed cities like Hong Kong, traffic impact is vitally important to plan the construction method, site layout implementation and working time. There is an urgent need for integrating traffic management into construction management. Temporary traffic management for a specific construction project can largely affect overall construction progress, the selection of construction methods for different work packages, and construction logistics management. For example, the selection of suitable construction method (e.g. open trench, microtunneling or pipe-jacking) to install underground utilities crossing a carriageway depends significantly on the impact upon traffic exerted by applying different methods. Integration of the construction model and the traffic model would benefit construction managers to determine the best construction scheme and method implementation details including temporary traffic management.

Second, the state of art in applying simulation modeling in construction remains much unchanged in the past decade: many issues identified ten years ago remain. For example, it takes too much time and too much learning to apply simulation; the results were not useful as it was too late to catch up with the field progress when field decision had been made. The mining case predicted the reliability of the proposed approach by comparing it with the state of the art in research and practice as of "today" throughout the trial run of the project. Discussions and adjustments were made during the project. In the case of microtunneling operations in Hong Kong, the twin micro-tunnel construction site offered a unique "test bed" for simulation modelling and model validation. As high computing power requirement will be demanded in simulating large civil engineering projects, remote high performance computers could be explored to increase the applicability of the construction simulation modeling. Remote high performance computers could be adopted as the simulation computing devices for executing multiple runs and scenario analysis with different sets of parameters, whereas the client computers will then be used as a computer platform for the model input and output analysis only. It is thus expected that shorter turnaround time for establishing and updating simulation models and higher modeling accuracy could be achieved in applying simulation modeling, which would in turn provide construction managers with sophisticated decision making support in running day-by-day construction operations in the field.

REFERENCES

1. AbouRizk, S. (2010). "Role of simulation in construction engineering and management." *J. Constr. Eng. Manage.*, 136(10), 1140-1153.

2. AbouRizk, S. and Hajjar, D. (1998). "A framework for applying simulation in construction." *Can. J. Civ. Eng.,* 25(3), 604-617.

3. AbouRizk, S. and Mohamed, Y. (2000). "Simphony: an integrated environment for construction simulation." *Proc. of the 32nd conf. on Winter simulation*, Society for Computer Simulation International, 1907-1914.

4. AbouRizk, S., Ruwanpura, J. Y., Er, K. C., and Fernando, I. (1999). "Special purpose simulation template for utility tunnel construction." *Simulation Conf. Proc., 1999 Winter,* IEEE, 2, 948-955.

5. AbouRizk, S. and Wales, R. (1997). "Combined discrete-event/continuous simulation for project planning." *J. Constr. Eng. Manage.*, 123(1), 11-20.

6. Bossink, B. and Brouwers, H. (1996). "Construction waste: quantification and source evaluation." *J. Constr. Eng. Manage.*, 122 (1), 55-60.

7. Chan, W. H. and Lu, M. (2005). "Logistics and operations simulation in precast viaduct construction: case study." *Proc. of the 2005 ASCE International Conf. on Computing in Civil Engrg*, 12.

8. Chan, W. H., and Lu, M. (2012). "Construction operations simulation under structural adequacy constraints: the Stonecutters Bridge case study." *Simulation Conf. (WSC), Proc. of the 2012 Winter*, 2961-2972.

9. Chan, W. H., and Lu, M. and Zhang, J. P. (2007). "Attaining cost efficiency in constructing sports facilities for Beijing 2008 Olympic games by use of operations simulation." *Proc. of the 38th conf. on Winter Simulation*, 2063-2070.

10. Chang, D. Y. and Carr, R. I. (1987). "RESQUE: A resource oriented simulation system for multiple resource constrained processes." *Proc. of the PMI Seminar/Symposium*, 4-19.

11. Chapman, D. N., Rogers, C. D., Burd, H. J., et al. (2007). "Trenchless technology research – Research needs for new construction using trenchless technologies." *Tunn. Undergr. Space Technol.,* 22(5), 491-502.

12. Chung, T. H., Abraham, D. M., and Gokhale, S. B. (2004). "Decision support system for microtunneling applications." *J. Constr. Eng. Manage.,* 130(6), 835-843.

13. De Vries, B. and Harink, J. M. (2007). "Generation of a construction planning from a 3D CAD model." *Autom. Constr.,* 16(1), 13-18.

14. Duran, X., Lenihan, H., and O'Regan, B. (2005). "A model for assessing the economic viability of construction and demolition waste recycling – the case of Ireland." *Resour. Conserv. Recycl.*, 46(3), 302-320.

15. Environment, Transport and Works Bureau (2002). *Environment, Transport and Works Bureau Technical Circular (Works) No. 33/2002 - Management of construction and demolition material including rock*, Hong Kong SAR Government.

16. Environment, Transport and Works Bureau (2005). *Environment, Transport and Works Bureau Technical Circular (Works) No. 19/2005 - Environmental management on construction sites*, Hong Kong SAR Government.

17. Gonzales-Quevedo, A. A., AbouRizk, S., Iseley, D. T., et al. (1993). "Comparison of two simulation methodologies in construction." *J. Constr. Eng. Manage.*, 119(3), 573-589.

18. Guy, B. (2001). "Building deconstruction assessment tool." *Deconstruction and Material Reuse: Technology, Economic, and Policy*, 125-136.

19. Guthrie, P., Woolveridge, A. C., and Patel, V. S. (1999). *Waste minimisation in construction: Site guide*, Constr. Industry Research and Information Association, London.

20. Hajjar, D. and AbouRizk, S. (1996). "Building a special purposes simulation tool for earth moving operations." *Proc. of the 28th conf. on Winter simulation*, IEEE, 1313-1320.

21. Hajjar, D. and AbouRizk, S. (1998). "Modeling and analysis of aggregate production operations." *J. Constr. Eng. Manage.*, 124(5), 390-401.

22. Hajjar, D. and AbouRizk, S. (2000). "Application framework for development of simulation tools." *J. Comput. Civ. Engrg.*, 14(3), 160-167.

23. Hajjar, D., AbouRizk, S., and Xu, J. (1998). "Construction site dewatering analysis using a special purpose simulation-based framework." *Can. J. Civ. Eng.,* 25(5), 819-828.

24. Hajjar, D., Mohamed, Y., and AbouRizk, S. (2000). "Creating special purpose simulation tools with Simphony." *Constr. Congress VI*, 87-96.

25. Halpin, D. W. (1977). “CYCLONE – method for modeling job site processes.” *J. Constr. Div.,* ASCE, 103(3), 489-499.

26. Halpin, D. W. (1990). *MicroCYCLONE user's manual.* Div. of Constr. Engrg. and Mgmt., Purdue Univ., West Lafayette, Ind.

27. Halpin, D. W. and Riggs, L. S. (1992). *Planning and analysis of Construction Operations.* John Wiley & Sons, Inc., New York.

28. Halpin, D. W., Jen, H. and Kim, J. (2003). “A construction process simulation Web service.” *Simulation Conf. 2003. Proc. of the 2003 Winter,* IEEE, 2, 1503-1509.

29. Huang, R. Y. and Halpin, D. W. (1993). “Dynamic interface simulation of construction operations (DISCO).” *Automation and Robotics in Constr,* 10, 503-513.

30. Ioannou, P. G. (1988). *“UM-Cyclone User's Guide.”* Tech. Rep. UMCE89-12, Civ. Engrg. Dept., Univ. of Michigan, Ann Arbor, Mich.

31. Kalk, A. (1980). *“INSIGHT: Internactive simulation of construction operations using graphical techniques.”* Tech. Rep. 238, Civ. Engrg. Dept., Standford Univ., Calif.

32. Kataoka, M. (2008). “Automated generation of construction plans from primitive geometries.” *J. Constr. Eng. Manage.*, 134(8), 592-600.

33. Kim, H., Anderson, K., Lee, S., et al. (2013). “Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology.” *Autom. Constr.,* 35, 285-295.

34. Kwong, M. H. C. (2003). "Sustainable development in civil engineering – the Hong Kong experience." *Proc. of the Second International Conf. on Constr. in the 21st Century (CITC-II) Sustainability and Innovation in Management and Technology,* Hong Kong, 15-19.

35. Lau, S. C., Lu, M., Ariaratnam, S. T., et al. (2008). "Uncertain factors and performance monitoring in trenchless construction operations." *12th International Conf. on Computing in Civil and Building Engrg* & *2008 International Conf. on Information Technology in Constr.*, Tsinghua Univ. Press, 265.

36. Lau, S. C., Lu, M., Ariaratnam, S. T., et al. (2009). "Development of intelligent decision support means for effective microtunneling construction planning." *Proc. of Global Innovation in Constr. Conf. 2009*, 556-565.

37. Lau, S. C. and Lu, M. (2010). "Simulation-based approach to planning temporary traffic arrangement for microtunneling operations in urban areas." *10th International Conf. on Constr. Applications of Virtual Reality 2010*, 395-404.

38. Lau, S. C., Lu, M., and Lo, K. (2010). "Planning pipe-jacking operations through simulation modeling based on a twin-tunnel microtunneling site in Hong Kong." *Proc. of 28th International No-Dig Conf. and Exhibition 2010*, 301-307.

39. Lau, S. C., Lu, M., and Poon, C. S. (2011). "Integration of construction and traffic engineering in simulating pipe-jacking operations in urban areas." *Proc. of the 2011 Winter Simulation Conf.*, IEEE, 3516-3525.

40. Lau, S. C., Lu, M., and Poon, C. S. (2013). “Modeling the production capacity of a continuous plant using discrete event simulation.” *Computing in Civil Engrg,* ASCE, 873-880.

41. Lau, S. C., Lu, M., and Poon, C. S. (2014). “Formalized approach to discretize a continuous plant in construction simulations.” *J. Constr. Eng. Manage*.

42. Lauritezen, E. K. and Hahn, N. J. (1992). “Building waste generation and recycling.” *International Solid Waste Management Association Year Book 1991-1992,* Cambridge, 48-58.

43. Law, A. M. and Kelton, W. D. (2000). *Simulation modeling and analysis*, McGraw-Hill, N.Y., 3rd ed., 87-89.

44. Lawson, N., Douglas, I., Garvin, S., et al. (2001). “Recycling construction and demolition wastes – a UK perspective.” *Environmental Management and Health*, 12(2), 146-157.

45. Liu, L. Y. and Ioannou, P. G. (1992). “Graphical object-oriented discrete-event simulation system.” *Proc. of the 24th conf. on Winter simulation,* ACM, 1285-1291.

46. Liu, H., Lei, Z., Li, H., et al. (2014). “An automatic scheduling approach: building information modeling-based on-site scheduling for panelized construction”. Accepted to *2014 Constr. Research Congress*.

47. Lluch, J. and Halpin, D. W. (1982). “Construction operations and microcomputers.” *J. Constr. Eng. Manage.,* 108(1), 129-145.

48. Lu, M. (2003). "Simplified discrete-event simulation approach for construction simulation." *J. Constr. Eng. Manage.*, 129(5), 537-546.

49. Lu, M., Anson, M., Tang, S. L., et al. (2003). "HKCONSIM: A practical simulation solution to planning concrete plant operations in Hong Kong." *J. Constr. Eng. Manage.*, 129(5), 547-554.

50. Lu, M., Chan, W., Zhang, J., et al. (2007a). "Generic process mapping and simulation methodology for integrating site layout and operations planning in construction." *J. Comput. Civ. Eng.*, 21(6), 453-462.

51. Lu, M., Lau, S. C., and Ariaratnam, S. (2009a). "Discussion of "Productivity study of microtunneling pipe installation using simulation" by Roy Yu Luo and Mohammad Najafi." *J. Infrastruct. Syst.*, 15(2), 133-135.

52. Lu, M., Lau, S. C., and Chan, E. K. Y. (2007b). "Combined simulation modeling using simplified discrete event simulation approach − a mining case study." *Proc. of the 2007 Summer Computer Simulation Conf.*, the Society of Modeling and Simulation, 421-428.

53. Lu, M., Lau, S. C., and Poon C. S. *(2009b). "Simulation approach to evaluating cost efficiency of selective demolition practices: case of Hong Kong's Kai Tak Airport demolition." J. Constr. Eng. Manage., 135(6), 448-457.*

54. Lu, M., Poon, C. S., and Wong, L. C. (2006). "Application framework for mapping and simulation of waste handling processes of construction." *J. Constr. Eng. Manage.,* 131(11), 1212-1221.

55. Lu, M. and Wong, L. C. (2007). "Comparison of two simulation methodologies in modeling construction systems: manufacturing-oriented PROMODEL vs. construction-oriented SDESA." *Autom. Constr.*, 16(1), 86-95.

56. Luo, R. Y. and Najafi, M. (2007). "Productivity study of microtunneling pipe installation using simulation." *J. Infrastruct. Syst.*, 13(3), 247-260.

57. Martinez, J. C. (1996). *STROBOSCOPE state and resource based simulation of construction processes*, Ph.D. Dissertation, Civil and Env. Engrg, Univ. of Michigan, Ann Arbor, MI.

58. Martinez, J. C. (1998). "Earthmover-simulation tool for earthwork planning." *Proc. of the 30th Winter Simulation Conf.,* IEEE, 2, 1263-1272.

59. Martinez, J. and Ioannou, P. G. (1994). "General purpose simulation with Stroboscope." *Proc. of the 26th conf. on Winter simulation,* Society for Computer Simulation International, 1159-1166.

60. Marzouk, M., Abdallahm, M., and El-Said, M. (2010). "Modeling microtunneling projects using computer simulation." *J. Constr. Eng. Manage.,* 136(6), 670-682.

61. Mohamad, Y. and AbouRizk, S. (2005). "Framework for building intelligent simulation models of construction operations." *J. Comput. Civ. Engrg.,* 16(3), 277-291.

62. Mok, W., Mak, M. and Poon, F. (2007). "Sewer installation by pipe jacking in the urban areas of Hong Kong, part II - performance of workers, lessons learned and improvement proposed." *The Hong Kong Institution of Engineers Transactions,* 14(1), 31-43.

63. Mok, W. and Mak, M. (2009). "Tunnelling and pipejacking techniques for trenchless installation of drainage pipelines." *The Hong Kong Institution of Engineers Transactions,* 16(2), 16-27.

64. Moon, H., Kim, H., Kamat, V., et al. (2013). "BIM-based construction scheduling method using optimization theory for reducing activity overlaps." *J. Comput. Civ. Eng.*

65. Myers, M. B., Stickrod, T. W., Abraham, D. M., et al. (1999). "Microtunneling technology for conduit construction." *Pract. Period. Struct. Des. Constr.,* 4(2), 56-63.

66. Nido, A. A., Knies, C. J. and Abraham, D. M. (1999). "Role of operation simulation in the analysis and improvement of microtunneling projects." *Tunn. Undergr. Space Technol.,* 14, 1-19.

67. Odeh, A. M., Tommelein, I. D., and Carr, R. I. (1992). "Knowledge-based simulation of construction plans." *Computing in Civil Engrg and Geographic Information Systems Symposium,* ASCE, New York, 1042-1049.

68. Oloufa, A. A. (1993). "Modeling operational activities in object-oriented simulation." *J. Comput. Civ. Eng.,* 7(1), 94-106.

69. Oloufa, A. A., Ikeda, M. and Nguyen, T. H. (1998). "Resource-based simulation libraries for construction." *Autom. Constr.,* 7(4), 315-326.

70. Paulson Jr, B. C., Chan, W. T., and Koo, C. C. (1987). "Construction operation simulation by microcomputer." *J. Constr. Eng. Manage.,* 113(2), 302-314.

71. Pidd, M. (1998). *Computer simulation in management science.* Chichester; New York: John Wiley, c1998. 4^{th} ed.

72. Poon, C. S., Yu, A. T. W., and Ng, L. H. (2001). "On-site sorting of construction and demolition waste in Hong Kong." *Resour. Conserv. Recycl.,* 32(2), 157-172.

73. Poon, C. S., Yu, A. T. W., Wong, S. W., et al. (2004). "Management of construction waste in public housing projects in Hong Kong." *Constr. Manage. Econom.,* 22(7), 675-689.

74. Pritsker, A. (1986). *Introduction to Simulation and SLAM II*, John Wiley and Sons, New York.

75. Pritsker, A. A. B. and O'Reilly, J. J. (1999). *Simulation with Visual SLAM and AweSim*, John Wiley and Sons, New York.

76. Rezazadeh Azar, E., Dickinson, S., and McCabe, B. (2013). "Server-customer interaction tracker: computer vision-based system to estimate dirt-loading cycles." *J. Constr. Eng. Manage.,* 139(7), 785-794.

77. Rezazadeh Azar, E. and McCabe, B. (2012). "Automated visual recognition of dump trucks in construction videos." *J. Comput. Civ. Eng.,* 26(6), 769-781.

78. Ruwanpura, J. Y. (2001). *Special purpose simulation for tunnel construction operations.* PhD Dissertation, Dept. of Civil and Env. Engrg, Univ. of Alberta, Edmonton, Alberta.

79. Ruwanpura, J. Y., AbouRizk, S., Er, K. C., et al. (2001). "Special purpose simulation templates for tunnel construction operations." *Can. J. Civ. Eng.,* 28(2), 222-237.

80. Ruwanpura, J. Y. and AbouRizk, S. (2001). "Design, development and application of soil transition algorithms for tunneling using special purpose simulation." *Proc. of the 33rd conf. on Winter Simulation,* IEEE, 1512-1520.

81. Ruwanpura, J. Y., AbouRizk, S., and Allouche, M. (2004a). "Analytical methods to reduce uncertainty in tunnel construction projects." *Can. J. Civ. Eng.,* 31(2), 345-360.

82. Ruwanpura, J. Y., Ariaratnam, S. T., and El-Assaly, A. (2004b). "Prediction models for sewer infrastructure utilizing rule-based simulation." *Civil Engrg and Environmental Systems,* 21(3), 169-185.

83. Ruwanpura, J. Y., and Ariaratnam, S. T. (2007). "Simulation modeling techniques for underground infrastructure construction processes." *Tunn. Undergr. Space Technol.*, 22(5), 553-567.

84. Seneviratne, A., Ruwanpura, J. Y., and Lueke, J. (2005). "Planning horizontal directional drilling projects using simulation." *Proc. of the No-Dig 2005 Conf.*

85. Shen L. Y., Tam V. W. Y., Tam C. M., et al. (2004). "Mapping approach for examining waste management on construction sites." *J. Constr. Eng. Manage.,* 130(4), 472-481.

86. Shewchuk, J. P. and Chang, T. C. (1991). "An approach to object-oriented discrete-event simulation of manufacturing systems." *Prod. of the 23rd Winter Simulation Conf.*, IEEE, 302-311.

87. Shi, J. S. (1999). "Activity-based construction (ABC) modeling and simulation method." *J. Constr. Eng. Manage.,* 125(5), 354-360.

88. Shi, J. S. and AbouRizk, S. (1998). "Continuous and combined event-process models for simulating pipeline construction." *Constr. Manage. Econom.,* 16(4), 489-498.

89. Sinfield, J. V. and Einstein, H. H. (1996). "Evaluation of tunneling technology using the "Decision aids for tunneling"." *Tunn. Undergr. Space Technol.*, 11(4), 491-504.

90. Song, L. and AbouRizk, S. (2006). "Virtual shop model for experimental planning of steel fabrication projects." *J. Comput. Civ. Eng.,* 20(5), 308-316.

91. Ueki, M., Haas, C. T., and Seo, J. (1999). "Decision tool for microtunneling method selection." *J. Constr. Eng. Manage.*, 125(2), 123-131.

92. Wang, W. C., Weng, S. W., Wang, S. H., et al. (2014). "Integrating building information models with construction process simulations for project scheduling support." *Autom. Constr.,* 37, 68-80.

93. Zayed T. M. and Halpin D. W. (2000). "Simulation as a tool for resource management." *Proc. of the 32nd Con. on Winter Simulation*, Society for Computer Simulation International, 1897-1906.