A DYNAMIC MODEL FOR ASSESSING THE EFFECTIVENESS OF CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT

YUAN HONGPING

Ph.D
The Hong Kong Polytechnic University
2011

The Hong Kong Polytechnic University

Department of Building and Real Estate

A Dynamic Model for Assessing the Effectiveness of Construction and Demolition Waste Management

YUAN Hongping

A thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

May, 2011

CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

Signature: ______________________

Name of student: YUAN Hongping

DEDICATION

To my Parents, younger Sister and younger Brother

To YI Langhua

ABSTRACT

It is widely accepted that a huge amount of waste is produced by construction activities every year throughout the world. This waste not only depletes finite landfill resources and contaminates the environment, but it also harms society. To help deal with the increasingly severe problems of waste generation in the construction industry, a plethora of studies have investigated construction and demolition (C&D) waste management. However, none of them developed a tool for assessing the performance of any given C&D waste management process.

This study used a system dynamics (SD) approach to examine the relationship of three measures of performance (economic, environmental, and social) that underlie the key variables of waste management practice. A literature review was conducted to identify the key variables, which the iThink SD simulation program then converted to stock-flow diagrams. The resulting model was validated using data collected from a construction project in China.

This study contributes to the body of waste management knowledge by having produced a holistic dynamic model that not only provides an improved understanding of how C&D waste management activities are dynamically influenced by the interactions of key variables, but is also capable of providing solutions for effectively controlling such variables.

PUBLICATIONS

1. Refereed Journal Papers

- Lu, W.S. and **Yuan, H.P.*** (2011). A framework for understanding construction and demolition waste management studies. ***Waste Management***, 31(6), 1252-1260.
- Lu, W.S., **Yuan, H.P.***, Li, J.R., Hao, J.L., Mi, X.M. and Ding, Z.K. (2011). An empirical investigation of construction and demolition waste generation rates in Shenzhen city, South China. ***Waste Management***, 31(4), 680-687.
- **Yuan H.P.*** and Shen, L.Y. (2011). Trend of the research on construction and demolition waste management. ***Waste Management***, 31(4), 670-679.
- **Yuan, H.P.***, Shen, L.Y. and Wang, J.Y. (2011). Major difficulties in improving the performance of waste management in China's construction industry. ***Facilities***, 29(5/6), 224-242.
- Wang, J.Y. and **Yuan, H.P.*** (2011). Major cost-overrun risks in construction projects in China. ***International Journal of Project Organization and Management***, 3(3/4), 227-242.
- Wang, J.Y. and **Yuan, H.P.*** (2011). Factors affecting contractors' risk attitudes in construction projects: case study from China. ***International Journal of Project Management***, 29(2), 209-219.
- Hao, J.L., Tam, V.W.Y., **Yuan, H.P.** and Wang, J.Y. (2011). Construction waste challenges in Hong Kong and Pearl River Delta Region. ***International Journal of Construction Management***, 11(1), 37-47. (Selected from CRIOCM2007 conference)
- **Yuan, H.P.***, Shen, L.Y., Hao, J.L. and Lu, W.S. (2011). A model for cost-benefit analysis of construction and demolition waste management throughout the waste chain. ***Resources, Conservation and Recycling***, 55(6), 604-612.
- Lu, W.S. and **Yuan, H.P.*** (2010). Exploring critical success factors for waste management in construction projects of China. ***Resources, Conservation and Recycling***, 55(2), 201-208.
- Hao, J.L., Tam, V.W.Y., **Yuan, H.P.**, Wang, J.Y. and Li, J.R. (2010). Dynamic modeling of construction and demolition waste management processes: an empirical study in Shenzhen, China. ***Engineering, Construction and Architectural Management***, 17(5), 476-492.
- Wang, J.Y., **Yuan, H.P.***, Ye, Y.C. and Ma, S.C. (2010). A multilevel grey model for assessing the sustainability of residential construction projects. ***Journal of Engineering Management***, 24(2), 196-201. [in Chinese]
- Wang, J.Y., **Yuan, H.P.***, Kang, X.P. and Lu, W.S. (2009). Critical success factors for on-site sorting of construction waste: a China study. ***Resources, Conservation and Recycling***, 54(11), 931-936.

- Wang, J.Y., **Yuan, H.P.*** and Liu, J. (2009). A factor analysis model for assessing the performance of the construction industry: the case of Shanghai. ***International Journal of Construction Management**,* 9(2), 21-31. (Selected from CRIOCM2007 conference)
- Wang J.Y. and **Yuan H.P.*** (2009). Construction waste management model based on system dynamics. ***System Engineering Theory & Practice***, 29(7), 173-180. [in Chinese]
- Wang J.Y. and **Yuan H.P.*** (2008). On-site construction waste management model based on system dynamics. ***Science & Technology Progress and Policy***, 25(10), 74-78. [in Chinese]

2. Refereed Conference Papers

- **Yuan, H.P.***, Hao, J.L. and Chini, A.R. (2011). Minimizing on-site construction waste through prefabrication in Hong Kong. *International Conference of Solid Waste 2011 Moving Towards Sustainable Resource Management (ICSWHK2011)*, May 2011, Hong Kong.
- Ye, G., **Yuan, H.P.*** and Wang, H.X. (2010). Estimating the generation of construction and demolition waste by using system dynamics: a proposed model. *The International Conference on Environmental Pollution and Public Health (EPPH2010)*, June 2010, Chengdu, China.
- Wang, H.X., Ye, G. and **Yuan, H.P.** (2010). An AHP/DEA methodology for assessing the productive efficiency in construction industry. *The 2010 International Conference on Engineering Management and Service Science (EMS 2010)***,** Aug. 2010, Wuhan, China.
- **Yuan, H.P.***, Lu, W.S. and Hao, J.L. (2009). A framework for integrating construction and demolition waste management studies. *The CRIOCM 2009 International Symposium on Advancement of Construction Management and Real Estate*, Oct. 2009, Nanjing, China.
- **Yuan H.P.***, Lu, W.S., Hao J.L. and Wang, J.Y. (2009). Implementing construction waste reduction strategies in Shenzhen, China". *First International Postgraduate Conference on Infrastructure and Environment*, June 2009, Hong Kong.

3. Book Chapters

- **Yuan, H.P.**, Wang, J.Y. and Shen, L.Y. (2010). ***Construction Supervision System in China***. In: Shen, L.Y., Leung, Y.P. and Hao, J.L. (Eds.) Construction and Real Estate Practice in China, pp. 85-93.
- Hao, J.L., **Yuan, H.P.** and Shen, L.Y. (2010). ***Practice of Joint Ventures***. In: Shen, L.Y., Leung, Y.P. and Hao, J.L. (Eds.) Construction and Real Estate Practice in China, pp. 188-194.
- Ochoa, J., **Yuan, H.P.** and Shen, L.Y. (2010). ***Sustainable Construction***. In: Shen, L.Y., Leung, Y.P. and Hao, J.L. (Eds.) Construction and Real Estate Practice in China, pp. 195-206.

ACKNOWLEDGEMENTS

Many people have contributed to the work which is accomplished in this thesis. Primary among them are my supervisory committee members. Each of them gives me a unique model from which I can learn and will create my own style for laying an academic road. First and foremost, I would like to express my deepest and most sincere appreciation to my supervisor, Professor Li-yin Shen, for his valuable support and guidance during this study. He has been an extraordinary mentor, leading my professional and personal growth throughout the Ph.D journey. And thanks for giving me an environment of sufficient freedom and valuing my research ideas. Dr. Jane J.L. Hao offered me a valuable opportunity to pursue my own interests in 2007. It is the offer that leads to my dedication to research. As one of the co-supervisors, her encouragement and kindness are unforgettable. Dr. Wilson, W.S. Lu, a very thoughtful and energetic scholar, has inspired me a lot during the past three years. His words “Ph.D is your own baby”, shared with me at the beginning of the journey, makes me reflect on the due attitude of raising my own Ph.D baby. His critical thinking in academic writing sets an example for pursuing excellence. Professor Edwin H.W. Chan, my former co-supervisor, has a distinctive sense of humor. He is also a respectable scholar. The experience of working with such a strong supervisory team not only witnesses a friendly supervisor-and-student relationship, but also, more importantly, becomes a precious fortune of my life.

I also would like to extend my gratitude to Professor Jia-yuan Wang of Shenzhen University. During this journey, he gives me valuable supports and plays an important role as a life-guider.

I owe thanks to Professor Abdol Chini of University of Florida. He offers me a valuable chance to visit US for six months. During the visit, he gives me great freedom to carry out independent research. It is also a great pleasure to work closely with him for a joint paper. Without this opportunity, I could never further my understanding of ‘research and life in the US’.

I also owe thanks to the guys in the big office – Room W606. The generous helps, the valuable friendship and the good-natured banter during meal breaks, all are indelible and make my life in BRE enjoyable.

I want to express my special thanks to BRE, HK PolyU, which not only offers the opportunity for me to pursue the doctoral degree, but also provides continual supports throughout the entire study.

I would like to gratefully acknowledge the people who participated in the case study for their valuable efforts and time.

Deepest gratitude goes to Yi Langhua and my family. My heartfelt thanks go to Yi Langhua because she always makes me reflect on my life when I am so engrossed in my own worries, anxieties and challenges that I forget the real reason why I work so hard for. She is somehow like my navigational light in the journey (☺). My family is forever the most comfortable home for me, both physically and spiritually. They have been silently supporting me in the pursuit of dreams for many years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 Introduction

1.1 Overview

1.2 Background of the research

1.3 Research problem statement

1.4 Aim and objectives

1.5 Research methodology

1.6 Significance of the research

1.7 Structure of the thesis

1.1 Overview

In line with the increasing acceptance of sustainable development as an important mission (WCED, 1987), the construction industry has recognized the need to alleviate its adverse impact on the environment and the consequent importance of waste management. Thus management for waste in the construction sector (generally termed ‘construction and demolition waste’ or ‘C&D waste’) has attracted widespread attention and become a recognized discipline in its own right. Many methods for managing C&D waste have been developed, such as establishing a waste management plan, adopting prefabrication, conducting on-site waste sorting, and using precise construction methods. However, there is a lack of a tool to help the industry understand and evaluate to what extent the application of such methods are effective. Without such a tool, it is difficult to assess the effectiveness of C&D waste management practices and subsequently improve them.

This thesis is the culmination of a PhD study aimed at developing a dynamic model for assessing the effectiveness of C&D waste management systems. This introductory chapter describes the background of the research, presents the research problem, defines the aim and objectives of the research, introduces the research methods to be adopted, and delineates the study’s contributions. The chapter concludes by outlining the structural arrangement between individual chapters in order to provide a general profile of the thesis.

1.2 Background of the research

(1) What is C&D waste?

C&D waste can be defined as waste which arises from construction, renovation and demolition activities including land excavation or formation, civil and building construction, site clearance, demolition activities, roadwork, and building renovation (HKEPD, 2007; Shen et al., 2004). The European Waste Catalogue (EWC, 2002) classifies C&D waste into the following eight categories: (1) concrete, bricks, tiles and ceramics; (2) wood, glass and plastic; (3) bituminous mixtures, coal tar and tarred products; (4) metals (including their alloys), (5) soil (including excavated soil from contaminated sites), stones and dredging spoil; (6) insulation materials and asbestos-containing construction materials; (7) gypsum-based construction material; and (8) other C&D waste. In Hong Kong, the composition of C&D waste is divided into two major categories: inert materials and non-inert waste (HKEPD, 2007). Inert materials comprise soft inert materials such as soil, earth and slurry, and hard inert materials such as rocks and broken concrete. Non-inert materials include waste such as metals, timber, plastics and packaging materials (Poon, 2007).

Municipal solid waste (MSW) is predominantly generated by domestic, commercial, and industrial activities and C&D waste takes up a significant proportion of it, for example: 29% in USA, 50% in the UK, 44% in Australia, 36% in Japan, and 38% in Hong Kong (HKEPD, 2006; Hendriks and CMRA, 2005).

(2) Impacts of C&D waste

Due to the huge volume of waste produced by various kinds of construction activities, the construction sector is perceived as a major culprit of environment degradation (Poon et al., 2004a; Faniran and Caban, 1998; Bossink and Brouwers, 1996). The United States Environmental Protection Agency (US EPA, 2002) estimated that approximately 136 million tons of building-related C&D debris is generated each year in the US, the majority from demolition and renovation (48% and 44% respectively). Sandler and Swingle (2006) found that only 20-30% of generated C&D waste in the US was recycled, while in the UK around 70 million tons of C&D materials and soil ended up as waste (DETR, 2000) producing a wastage rate in the UK construction industry of 10-15% (McGrath and Anderson, 2000). In Australia, nearly one ton of solid waste was sent to landfill per person each year (Reddrop and Ryan, 1997), and C&D waste was estimated to account for 16%-40% of total MSW (Bell, 1998). In Hong Kong, the C&D waste generated annually more than doubled between 1993 and 2004 (Poon, 2007). According to a report by Hong Kong's Environment Protection Department, about 2900 tons of C&D waste was received at landfills per day in 2007 (HKEPD, 2007). Furthermore, in 2008, China produced 29% of the world's MSW, of which construction activities contributed nearly 40% (Wang et al., 2008).

Society is influenced by C&D waste from an economic perspective, an environmental perspective, and a social perspective. The economic impact on society of C&D waste management encompass: investment in C&D waste collection, separation and sorting costs; cost of purchasing equipment; economic benefits from managing C&D waste; cost of landfills; and profits from waste recycling. Environmental impacts include: loss of habitat when pristine land is used for new landfills or there are expansions of existing landfills; increased extraction of raw materials for new construction products; seeping from landfill items into soil and groundwater; and poor air quality from demolition activities that increase dust and noise levels. Social impacts involve increased job opportunities, opportunities for job training, and community involvement in reshaping local built environments.

(3) Overview of C&D waste management research and practices

Since the early 1980's, widespread attention has been paid to finding effective measures to minimize C&D waste in order to slow down degradation of the environment and alleviate the consequential negative impacts on society. This has led to a plethora of papers having been published in various academic journals based on investigations into a vast array of topics related to C&D waste management.

After reviewing C&D waste management publications between 1986 and 2010, Lu and Yuan (2011) concluded that research and practices regarding C&D waste management can be better understood by putting them into a *C&D Waste Management Spectrum* (Figure 1.1), which ranges from *hard* construction technologies to *soft* waste management measures. Hard construction technologies, comprising environmentally friendly building technologies and environmental engineering technologies, are often the preferred approach for managing C&D waste. They include prefabrication, steel formwork, and recycled aggregates (Poon and Chan, 2007), as well as technologies for dealing with air, water and soil pollution caused by the production of carbon dioxide and methane from the anaerobic degradation of C&D waste disposed of at landfills. Soft waste management measures comprise various economical/managerial instruments based on the view that C&D waste management is also a social issue.

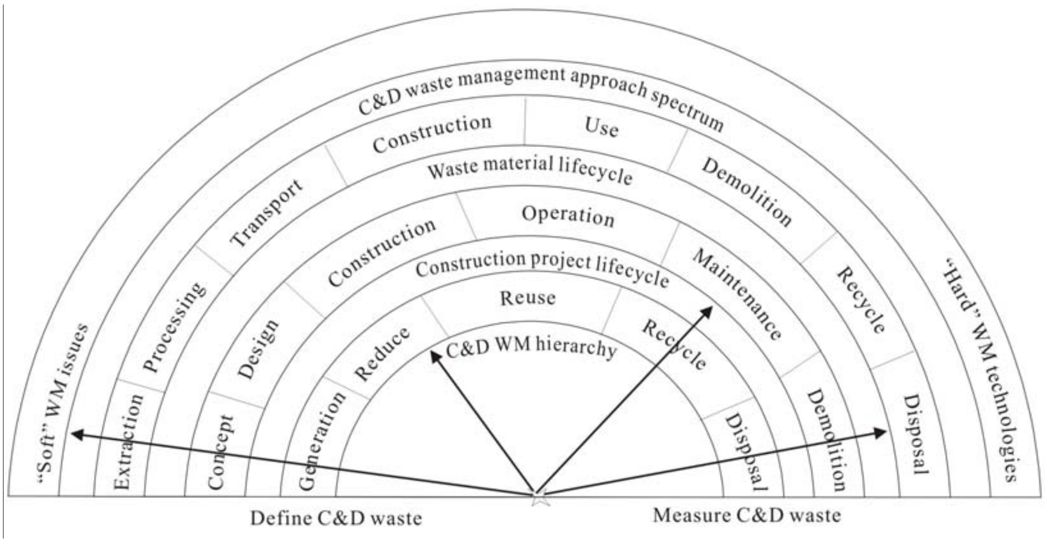

Figure 1.1: A framework of C&D waste management research

[Source: Lu and Yuan (2011)]

Most C&D waste management studies used questionnaire, interview, various modeling techniques, and descriptive analysis based on statistical results (Yuan et al., 2010). Other research examined both technical and managerial aspects of C&D waste management. For example, Jallion and Poon (2008) examined the technical, managerial and marketing aspects of prefabrication technology in Hong Kong and concluded that the hard technologies and soft economical/managerial instruments can be mutually enhanced to deal with C&D waste more effectively.

(4) Key characteristics of C&D waste management

Yuan and Shen (2011) determined that a lack of appreciation of established approaches to C&D waste management hinders a proper understanding of their effectiveness. This might be partly due to the fact that studies have not hitherto taken account of the key characteristics of C&D waste management when assessing the effectiveness of C&D waste management practices. These characteristics include:

- *C&D waste management is complicated:* The complicated nature of C&D waste management can be demonstrated by the variety of activities involved. As shown by Figure 1.1, generation, reduction, reuse, recycling, and disposal are all activities involved in C&D waste management, and, as pointed out by Yuan and Shen (2011), each of the activities involves different stakeholders. Therefore, an interdisciplinary approach that can deal with all the activities of a system is desirable to ensure that the goals of C&D waste management are fully met (Graham and Smithers, 1996).
- *Activities within C&D waste management are largely interdependent*: In conventional C&D waste management, waste generation, reduction, reuse, recycling and disposal are treated as independent activities. However, all of them are closely interlinked and each activity can influence the others (Seadon, 2010). Clark (1978) argued that effective management of C&D waste should envisage the interdependent nature of activities and maintain a balance between them.
- *C&D waste management is dynamic*: Conventional C&D waste management research tends to view C&D waste management as a static process rather than a dynamic one (Yuan et al., 2010).

In order to understand a complicated C&D waste management system from a holistic perspective, it is necessary to consider the dynamic interrelationship among the variables within the system. In other words, only by recognizing the complexities of C&D waste management is it possible to assess the effectiveness of systems and subsequently improve them.

1.3 Research problem statement

(1) How to assess the overall effectiveness of C&D waste management systems by envisaging its key characteristics

The preceding section has shown that the dynamics and interrelationships involved in C&D waste management have an important role to play in assessing the effectiveness of C&D waste management practices. However, previous studies associated with C&D waste management have concentrated their efforts on examining C&D waste management systems from a static point of view, without considering the dynamic relationship of interrelated variables involved in the systems. Therefore, to better understand, assess and improve the effectiveness of C&D waste management, a systematic approach that is capable of dealing with the complexities of C&D waste management systems is required.

In this study, the relationships among various C&D waste management activities were considered from a system dynamics (SD) perspective. The major influence of variable interactions on the whole system could be described with SD because it portrays only the key behaviors of the system. Through identifying essential variables affecting the effectiveness of C&D waste management, a conceptual model was developed to describe their causes-and-effect relationships in a C&D waste management system. The model offers a way to integrate a series of causality activities within a C&D waste management system by considering the interactions of each activity rather than a simple stimulus-response action.

(2) Scope of this study

C&D waste as an integral term has been assigned different meanings in previous studies. For example, the term used in Wang et al. (2004a) refers to waste caused by both new building construction and demolition activities, while C&D waste in Fatta et al. (2003) refers to a much broader range of materials including excavation materials, road planning and maintenance materials, demolition materials, and worksite waste materials. As pointed out by Lu and Yuan (2011), each study tends to define C&D waste based on the characteristic of its research question. However, only by defining the term specifically can results of a study be meaningful for different practices. In view of the fact that the overall aim of this study was to develop a dynamic model for assessing the effectiveness of C&D waste management, C&D waste was considered to be material waste caused by building construction and demolition activities. Thus, the *C&D waste* for this study is defined as follows:

> C&D waste refers to the byproduct produced during the process of construction and demolition of building structures; components of C&D waste typically include concrete, asphalt, wood, metals, gypsum wallboard, and plastic.

It can be seen from Figure 1.1 that from a lifecycle perspective, material waste in the construction industry might arise from a number of processes including: raw material extraction, processing, transporting materials to construction sites for use, building structures, use, demolition, recycling and disposal. However, as it was not practical to include all of these processes in this study due to resource and time constraints, the investigation was confined to the widely recognized C&D waste management hierarchy of waste generation, reduction, reuse, recycling, and disposal.

As mentioned in Section 1.2, existing studies in relation to C&D waste management applied both *soft* (economical/managerial) measures and *hard* technologies. Hard technologies were beyond the scope of this study. The effectiveness of C&D waste management systems was examined by three measures of performance: economical performance, environmental performance, and social performance. Although a SD modeling technique was employed, the research focused primarily on the presence of economical/managerial measures for dealing with the effectiveness of C&D waste management.

1.4 Aim and objectives

The principal aim of this research was to develop a model for assessing the effectiveness of C&D waste management using a SD approach. The model describes the dynamic interactions among different activities within C&D waste management systems and provides a tool for evaluating and improving the effectiveness of C&D waste management.

The specific objectives devised in order to help achieve the aim were as follows:

(1) To identify major variables affecting the effectiveness of C&D waste management systems;

(2) To construct a dynamic model for evaluating the effectiveness of C&D waste management systems;

(3) To validate the established model and demonstrate its application; and

(4) To analyze a series of management scenarios for improving the effectiveness of C&D waste management systems.

The following section describes the methodology of how these objectives were achieved.

1.5 Research methodology

A well-designed research plan ensures that research activities proceed smoothly, and an appropriate research methodology can ensure the accomplishment of the research objectives. Accordingly, a research plan, comprising the research objectives, the research activities for achieving each of the objectives, and the research methods adopted for research activities was developed to help accomplish the aim of the research.

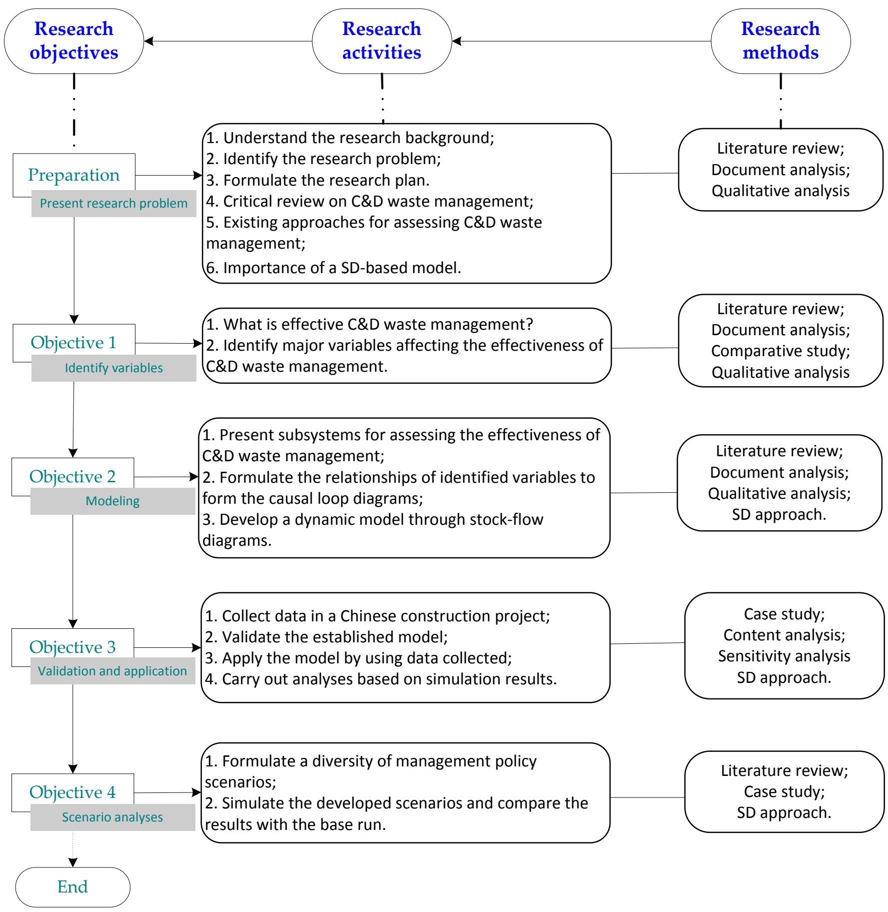

Figure 1.2: Research plan

(1) Research activities and methods

As can be seen from Figure 1.2 above, each of the four research objectives was realized by a variety of research activities, and that the main research methods encompassed literature review, document analysis, qualitative analysis, comparative study, case study, content analysis, sensitivity analysis and SD approach. A detailed description of how each of these research objectives was achieved is elaborated below.

Preparation stage: To present the research problem.

Research activities: (1) understand the research background; (2) identify the research problem; (3) formulate the research plan; (4) review C&D waste management research; (5) review existing approaches for evaluating C&D waste management; (6) analyze the importance of developing a SD-based model;

Methodology: Literature review; document analysis; qualitative analysis.

The foremost task at the preparation stage is identification of a significant topic. As there is a plethora of published studies covering a vast array of topics relating to C&D waste management, it was difficult to formulate a research problem that would be both theoretically and practically significant. However, the researcher was able to draw upon his experience of having studied C&D waste management for his master's degree, to make the process of understanding the research background and identifying the research problem more efficient. Based on the research problem, which was to develop a dynamic model for assessing the effectiveness of C&D waste management systems, a detailed research plan was developed.

A critical literature review of C&D waste management was also carried out, to identify knowledge gaps and provide a clear understanding of the academic context in which the research was to be conducted. The review also provided an explicit appreciation of the study's contribution to the body of knowledge.

During the review, particular attention was given to comparing the various approaches adopted for evaluating C&D waste management systems. The rationale for this activity was the need to highlight the SD approach while attempting to understand and assess the effectiveness of C&D waste management.

Objective 1: To identify major variables affecting the effectiveness of C&D waste management systems.

Research activities: (1) what is effective C&D waste management? (2) identify major variables affecting the effectiveness of C&D waste management systems.

Methodology: Literature review; document analysis; comparative study; qualitative analysis.

The major task of Objective 1 was to formulate a series of variables that significantly affect the effectiveness of C&D waste management. These variables laid the foundation for subsequent model development. This was achieved by undertaking the research activities outlined below.

In order to efficiently identify the key variables involved in assessment of the effectiveness of C&D waste management systems, it was necessary to first determine the meaning of the term ‘effective C&D waste management’ in the context of the study. Then the key variables were identified through examining the characteristics of C&D waste management activities and considering their inherent connections, analyzing guidelines and reports, and deriving research data from previous studies.

Objective 2: To construct a dynamic model for evaluating the effectiveness of C&D waste management systems.

Research activities: (1) present sub-systems for assessing the effectiveness of C&D waste management; (2) formulate the relationships of identified variables to form causal loop diagrams; (3) develop a dynamic model through stock-flow diagrams.

Methodology: Literature review; document analysis; qualitative analysis; SD approach.

This part of the study established a system for assessing the effectiveness of C&D waste management, established its specific boundaries, and developed the underlying sub-systems.

A series of ‘causal loop diagrams’ were next developed to portray the dynamic chains of causes and the relationships among the variables in the system. These causal loop diagrams served as a conceptual model to show how the system is dynamically influenced by the interaction of all the variables. The dynamic behavior of the model is determined by the feedback loops contained in the causal loop diagrams.

Finally, with the aid of the iThink software package, which is specifically designed for SD modeling, the causal loop diagrams were used as the basis for developing a stock-flow simulation model to perform quantitative analysis.

Objective 3: To validate the established model and demonstrate its application

Research activities: (1) collect data from a construction project in China; (2) validate the established model; (3) apply the model by using the data collected; (4) carry out analyses based on simulation results.

Methodology: Case study; content analysis; sensitivity analysis; SD approach.

This research objective was mainly achieved through four research activities. Firstly, a practical case selected from the Chinese construction industry was introduced for supporting the data required for model validation and application.

Data for the variables were obtained by means of site survey consisting of a series of formal and informal meetings and communication with five on-site staff, including one project manager, one on-site manager, one on-site technical engineer and two supervisory engineers. The variables used in the model were divided into three categories: quantitative variables, qualitative variables, and dependent variables. The method used for quantifying each category of variable is elaborated in Section 6.4.

The established model was tested and validated by following guidelines suggested by Coyle (1996) that help to build confidence in SD models. A series of sensitivity analyses were also carried out to check how the model behaved and responded to a change in a variable.

Finally, the model was simulated by inputting data for all the variables and the subsequent results analyzed. The simulation was carried out using iThink software.

Objective 4: To analyze a series of management policy scenarios.

Research activities: (1) formulate a diversity of management policy scenarios; (2) simulate the developed scenarios and compare results with those of the base run.

Methodology: Literature review; case study; SD approach.

In this research activity, a series of scenarios were designed to evaluate the influence of different hypothetical waste management policies. The management policies were based on an extensive review on related studies. Scenario simulation and analyses were conducted through the ‘policy laboratory function’ provided by SD modeling. Two broad types of policy scenarios were simulated. One type adopted different value combinations of Wecpv (weight of economic performance value), Wenpv (weight of environmental performance value) and Wsopv (weight of social performance value). This helped deepen the understanding of how the effectiveness of C&D waste management in the same construction project would change when different measures of economic performance, environmental performance, and social performance are proposed by different decision-makers. The other type of policy scenario is to understand the effects of applying different waste management policies for minimizing C&D waste.

All the management scenarios were simulated and the results compared with those of the base run. Based on the comparisons recommendations were then presented for ameliorating the effectiveness of C&D waste management.

1.6 Significance of the research

The significance of this research is as follow:

(1) The study is meaningful due to its contribution to the body of knowledge of C&D waste management. The study has constructed a simulation model capable of integrating all the key variables related to the effectiveness of C&D waste management. The model can assist decision-makers responsible for assessing and improving the effectiveness of waste management in a particular construction project.

(2) Through portrayal of the interrelationships between various variables, the dynamic features of a C&D waste management system can be better understood. The study further also contributes to the application of the SD approach to the discipline of C&D waste management and provides a platform for further studies and debate.

(3) From a practical perspective, this study provides contractors with a tool with which to test different waste management measures before implementing them. The simulation model allows numerous attempts at discovering ways to improve the effectiveness of waste management in any given construction project.

1.7 Structure of the thesis

This thesis consists of eight chapters. **Chapter 1** describes the background of the research, explains the study's aim and objectives, outlines the research methodology, and presents the structure of the thesis.

Chapter 2 reviews the literature relating to C&D waste management research. The topics covered include the concept of C&D waste, research into C&D waste generation, strategies for managing C&D waste, and project stakeholders' attitudes toward C&D waste management. Approaches adopted for assessing C&D waste management are also reviewed.

Chapter 3 identifies major variables affecting the effectiveness of C&D waste management systems. The variables are mainly concerned with waste generation, economic performance, environmental performance, and social performance as they relate to C&D waste management.

Chapter 4 introduces the SD approach including its theoretical concept, essential elements for constructing a model, the modeling procedure, and the iThink software package used for model simulation.

Chapter 5 focuses on the development of a dynamic model for assessing the effectiveness of C&D waste management systems. A variety of causal loop diagrams depicting the relationships among key variables are presented and a stock-flow diagram developed using the iThink software.

Chapter 6 presents the data collected from a construction project in China for demonstrating the validity and application of the SD simulation model.

Chapter 7 analyzes the simulation results of a series of management policy scenarios.

Chapter 8 provides an overall summary of the study including major conclusions, findings, contributions, limitations, and recommendations for future research.

CHAPTER 2 Literature Review

2.1 Introduction

This chapter presents a review of the literature related to C&D waste management. The chapter first considers the meaning of the term ‘C&D waste’ followed by an examination of some typical issues relating to C&D waste generation, such as reporting C&D waste, origins of C&D waste, and ways of measuring the performance of C&D waste management systems. It then reviews the strategies adopted for minimizing C&D waste and presents major stakeholders’ attitudes toward C&D waste management. The chapter concludes by identifying important limitations in current literature and provides an appreciation of knowledge gaps and a justification for this study’s use of the SD approach.

2.2 Definition of C&D waste

There is a lack of consensus in the literature over the definition of C&D waste. C&D waste had been defined as the waste that arises from construction, renovation and demolition activities (Kofoworola and Gheewala, 2009). This may include surplus and damaged products and materials arising in the course of construction work or used temporarily during the process of on-site activities (Roche and Hegarty, 2006). Similar definitions of C&D waste can be found in Hao et al. (2007a), Shen et al. (2004) and Fatta et al. (2003).

The European Waste Catalogue (EWC, 2002) provides a comprehensive classification of C&D waste in line with its compositions. Although C&D waste is often included as one of the forms of MSW, it is considered to be heterogeneous compared with the general MSW (e.g. household waste) or other industrial solid wastes (e.g. hospital waste and computer waste).

Different perspectives on C&D waste imply different waste management philosophies. In Japan, C&D waste is considered as a *by-product* of construction rather than *waste* and as such great emphasis is placed on reuse and recycling (Nitivattananon and Borongan, 2007). Each study tends to define C&D waste based on the characteristic of its research question because only by defining the waste specifically can results of a study be meaningful for different practices (Lu and Yuan, 2011).

The term C&D waste is increasingly used in the literature. From a landfill perspective this term can be reasonably used to stand for all solid waste even though construction waste and demolition waste are considerably different in terms of their volumes (Li, 2006; US EPA, 2002; Bossink and Brouwers, 1996). The concept of C&D waste is therefore that it should represent material waste from all construction activities, regardless of whether it originates from construction or demolition activities.

While some studies defined the term C&D waste by viewing it as tangible wasted materials, there is another stream of research suggesting that C&D waste should include non-value-adding construction work (Serpell and Alarcon, 1998). This viewpoint can be traced back to an early study by Skoyles (1976) who made a distinction between direct and indirect C&D waste by suggesting that direct waste is direct material loss, whilst indirect waste is a monetary loss such as may occur if the thickness of a concrete slab is greater than specified. This view, supported by Formoso et al. (2002) and Serpell and Alarcon (1998), enables researchers to consider both the material loss and the non-value-adding work. However, recent studies appear to have overlooked this approach to C&D waste, probably because waste materials in construction are easy to see, as well as relatively easy to measure (Formoso et al., 2002).

Whilst there are various definitions about C&D waste, they share the common understanding that these waste come from various processes in both construction and demolition activities. These definitions serve for purposes of carrying out individual studies. Thus this research defined, as in Section 1.3, that C&D waste refers to the byproduct produced during the process of construction and demolition of building structures; components of C&D waste typically include concrete, asphalt, wood, metals, gypsum wallboard, and plastic.

2.3 C&D waste generation

2.3.1 Amount of C&D waste

There are numerous reports concerning the amount of C&D waste generated in various countries and regions. For example, Mills et al. (1999) reported that the US construction industry generated over 100 million tons of C&D waste annually, and Rogoff and Williams (1994) reported that approximately 29% of solid waste in the U.S. is from the construction sector. In the UK, C&D waste consumes more than 50% of the overall landfill volume (Ferguson et al., 1995) and 70 million tons of C&D waste is discarded annually (Sealey et al., 2001). Craven et al. (1994) [cited in Shen et al., 2004] reported that construction activities generate about 20%-30% of all waste entering Australian landfills. In Hong Kong, about 38% of the solid waste comes from the construction industry (Tam, 2008a), and between 1993 and 2004 the annual generation of C&D waste in Hong Kong more than doubled, reaching an amount of about 20 million tons in 2004 a single year (Poon, 2007). Tam (2008a) reported that C&D waste forms 19% and 14% of the waste disposed of at landfills in Germany and Finland, respectively.

The above statistics provide an indication of the proportion of C&D waste as a percentage of total solid waste generated in some typical economies. However, when the waste generated from new construction and the waste generated from demolition is considered separately, it is evident that the volume of waste generated from demolition activities is more than that from construction activities. Data released by Bossink and Brouwers (1996) showed that the annual volumes of C&D waste in Germany was estimated at 30 million tons for demolition waste and 14 million tons for construction waste, whilst a report by the US EPA (2002) mentioned that the majority of C&D waste was from demolition and renovation, which was 48% and 44% respectively.

Without accurate and timely data on C&D waste generation, the general public would not realize the situation facing societies and the industry could not be persuaded of the pressing need to manage C&D waste. Over the past few decades, C&D waste and its adverse impact on the environment have attracted widespread attention from researchers and industry practitioners. However, some countries, notably China (Wang et al., 2008), Malaysia (Begum et al., 2007a), Turkey (Esin and Cosgun, 2007) and Thailand (Kofoworola and Gheewala, 2009), are lagging behind in reporting the amount of C&D waste that they generate.

2.3.2 Origins of C&D waste

C&D waste originates from various sources throughout the life cycle of construction projects, from inception through to construction and demolition (Shen et al., 2004). According to previous studies, the origins of C&D waste can be classified into the following ten categories: contractual, design, procurement, transportation, on-site management and planning, material storage, material handling, site operations, residual, and other causes (Osmani et al., 2008; Kulatunga et al., 2006; Gavilan and Bernold, 1994). These origins are shown in Table 2.1 below.

Table 2.1: Origins and causes of C&D waste

Origins of waste	Causes of waste
Contractual	Errors in contract documents
	Contract documents incomplete at commencement of construction
Design	Design changes
	Design and detailing complexity
	Design and construction detail errors
	Unclear/unsuitable specification
	Poor coordination and communication (late information, last minute client requirements, slow drawing revision and distribution)
	Selection of low-quality products
	Lack of attention to standard sizes available on the market
	Designers' unfamiliarity with alternative products
Procurement	Ordering errors (i.e., ordering items not on compliance with specification)
	Over allowances (i.e., difficulties to order small quantities)
	Supplier errors
	Purchased products that do not comply with specification
Transportation	Damage during transportation
	Difficulties for delivery vehicles accessing construction sites
	Insufficient protection during unloading

	Inefficient methods of unloading
On-site management and planning	Lack of on-site waste management plans
	Improper planning for required quantities
	Delays in passing information on types and sizes of materials and components to be used
	Lack of on-site material control
	Lack of supervision
Material storage	Inappropriate site storage space leading to damage or deterioration
	Improper storage methods
	Materials stored far away from point of application
Material handling	Materials supplied in loose form
	On-site transportation methods from storage to the point of application
	Inadequate material handling
	Damages during transportation
	Unfriendly attitude of project team and laborers
Site operation	Accidents due to negligence
	Unused materials and products
	Equipment malfunction
	Poor craftsmanship
	Use of wrong materials resulting in their disposal
	Time pressure
	Poor work ethics
Residual	Waste from application processes (i.e., over-preparation of mortar)
	Off-cuts from cutting materials to length
	Waste from cutting uneconomical shapes
	Packaging
other	Weather
	Vandalism

	Theft

(Sources: Osmani et al., 2008; Kulatunga et al., 2006; Gavilan and Bernold, 1994)

Amongst these categories, origins such as contractual, design, and procurement, will cause indirect C&D waste because their effects will only be observed during the construction stage. This suggests that in order to effectively reduce C&D waste at source, C&D waste management strategies should embrace lifecycle thinking rather than merely concentrating on the construction stage.

Design changes occurring during construction are widely recognized as the most significant source of C&D waste (Ekanayake and Ofori, 2004; Faniran and Caban, 1998). This concurs with a finding from Osmani et al.'s (2008) study that approximately 33% of on-site waste is related, either directly or indirectly, to project design. Changes to the original project design can cause waste in two ways. Firstly, if the construction materials have already been purchased on the basis of the original design, waste could be caused if the material cannot be resold or returned to the supplier and has to be disposed of. Secondly, a design change in part of a structure that has already been built might result in that part having to be dismantled with a subsequent waste of the material that cannot be salvaged for reuse (Faniran and Caban, 1998). Project design associated with C&D waste generation is complex due to the usage of a wide variety of materials and the involvement of stakeholders other than the designers, such as clients and contractors (Osmani et al., 2008). Such complexity results in very few attempts to find solutions for minimizing C&D waste during project design (Osmani et al., 2006), and is probably the main barrier to effective C&D waste minimization at the project design stage.

2.3.3 Measuring C&D waste

Efforts have been made to report C&D waste as a percentage of total MSW so that comparisons can be made in order to discover the reasons for high or low waste generation rates (WGR). For example, Tam (2008a) found that C&D waste formed 19% and 14% of the waste disposed of at landfills in Germany and Finland respectively, whilst in Hong Kong it was about 38%. However, these comparisons should be treated with caution because the percentages are influenced not only by construction activities but also by the size of a country/region's economy and population, as well as its social behavior. Generally, researchers consider WGR to be a good comparator.

The investigation of WGR has long attracted construction researchers as well as practitioners. Table 2.2 is a summary of some previous studies pertaining to the investigation of WGR. Skoyles (1976) conducted a study based on data from 114 building sites during the 1960s and 1970s. He examined WGR for 37 materials in the UK through direct on-site observation and by comparing contractors' records. Results showed that the percentage of waste materials ranged from 2% to 15% in weight in relation to the materials specified by the design. The first extensive investigation of WGR in Hong Kong was carried out by Poon et al. (2001a) who, between June 1992 and February 1993, investigated 32 construction sites. The report revealed that the rate of packaging waste was as high as 5% of the volume of materials and that WGR of premixed concrete ranged from 2.4% to 26.5%. A series of studies was led by Poon et al. (2004a, 2004b, 2004c) to investigate WGR of various construction materials in Hong Kong. McDonald and Smithers (1998) conducted a study on WGR in Australia by comparing waste management practices in two projects and produced figures showing the waste percentage for various materials, including steel, non-ferrous metals, glass, paper, concrete, packaging, plasterboard, plastics, insulation, timber, general sweepings and carpet. Bossink and Brouwers (1996) studied WGR in the Netherlands by using three different measurements, namely, the quantity of a particular type of C&D waste as a percentage of total amount of C&D waste, C&D waste as a percentage of total purchased specific material (by weight), and cost of a particular type of C&D waste as a percentage of total waste costs. By comparing the figures with those in other countries, the consequence of using different construction techniques, work procedures, and common practices were identified. Pinto (1989) [cited in Formoso et al., 2002] estimated both direct and indirect waste of 10 building materials in Brazil and found that the percentage of wasted materials ranged from 1% to 102% in relation to the total weight of materials specified by the design; the total WGR was 18% of the weight of all materials purchased, which added 6% to the overall cost. Years later, similar findings were arrived at by Formoso et al. (2002) who studied the WGR of 8 materials in Brazil based on contractors' material supply records and direct observations; a high variability of performance was found for all materials with the WGR of cement ranging from 6.4% to 247.1% in a sample of 41 building sites. Finally, Tam et al. (2007a) assessed the affect of sub-contracting relationships and projects types on WGR. All these studies provide valuable insights into WGR in various economies and make comparisons possible.

Table 2.2: A summary of previous studies on WGR

Author	Country	Measurement of WGR	Methodology	Main conclusions
Skoyles (1976)	UK	Percentage by weight (of the amount required according to design)	Direct observation and comparing contractors' records	2%-15% by weight according to the amount purchased for 37 materials
McGregor et al. (1993)	USA	Weight and percentage of total waste from an individual project	Questionnaire and telephone survey	Varied with construction type and project cost
Bossink and Brouwers (1996)	Netherland	Percentage by weight (of purchased materials)	Sorted and weighed the waste materials	1%-10% by weight of the amount purchased for 7 materials, with an average of 9%
McDonald and Smithers (1998)	Australia	The volume (m^3) of waste generated per m^2 of gross floor area	Sort in waste bins and delivery records of bins	Total waste rate: 0.084 m^3/m^2
Forsthe and Marsden (1999)	Australia	Waste = ordered materials - in-situ quantities	In-situ quantities were from drawing or site measurement; ordered materials were from delivery and order documents	Maximal and minimal generation rate for 8 materials by percentage in two projects
Poon et al. (2001a)	Hong Kong	Percent by weight or volume according to	Site observation and	1-8% for public housing; 1-100%

		different materials	questionnaire	for private housing
Morris Specifications Inc. (2001)	Canada	N/A	N/A	WGRs for main construction materials (wood, drywall, metal, concrete, other) are given
Formoso et al. (2002)	Brazil	Waste (%) = [(Mpurchased-Inv)-Mdesigned]/Mdesigned; Where Inv indicates the final inventory of materials	Direct observation and contractors' records	19.1%-91.2% by weight according to the amount purchased for 8 materials
Treloar et al. (2003)	Australia	Not clear	Consultation with construction company employees	3%-10% for eight materials
Poon et al., (2004a)	Hong Kong	The volume (m^3) of waste generated per m^2 of gross floor area	Visual inspection, tape measurement, truck load records	The total waste generation rate: 0.176 m^3/m^2 (C); 0.4-0.65 m^3/m^2 (D)
Lin (2006)	Taiwan	The volume (m^3) of waste generated per m^2 of gross floor area	The Neural Network Method	0.85 m^3/m^2 for factory (D); 0.54-0.66 m^3/m^2 for residential (D)
Tam et al. (2007b)	Hong Kong	Wastage level (%T) =(Mp -Mu)/Mu ×100; where Mp is the purchased material and	Interview with people involved in the industry	8.9-20% and 4.11-6.62% by weight for 5 materials according to

		Mu is the used material (in m^3 for concrete, in ton for reinforcement, in m^2 for formwork, in m^2 for brick/block and in m^2 for tile).		different sub-contracting arrangement

It is can be clearly seen from Table 2.2 that previous studies have adopted different measures for WGR. Waste is measured by weight (kg, ton) or by volume (m^3). The rates are calculated by dividing waste by the amount purchased, the required in design, or per m^2 of gross floor area (GFA). Therefore, by combining different measurements, there are four typical measurements for WGR: (1) percentage of purchased, (2) percentage of required by design, (3) kg/m^2 of GFA, and (4) m^3/m^2 of GFA. This is largely in accordance with the waste measures summarized by Formoso et al. (2002). The measures should be appropriate for different materials with different properties. For example, Skoyles (1976) and Tam et al. (2007b) engaged a unit of m^3 for concrete, ton for reinforcement, m^2 for formwork, m^2 for brick/block, and m^2 for tile. Certainly, *one size does not fit all*; the measures should also be appropriate for different purposes and no one measure is any better than another. For example, by multiplying the rates in kg/m^2 of GFA or m^3/m^2 of GFA by total GFA, it is possible to calculate the total amount of waste generated. By analyzing the rate as a *percentage of purchases*, it is possible to assess the effectiveness of the purchasing department, logistics management, and material storage.

Methodologies adopted for obtaining data for estimating the WGR are diverse. These methods typically include direct observation (Poon et al., 2001a, 2004a; Skoyles, 1976), comparing contractors' records (Skoyles, 1976), questionnaire and telephone survey (McGregor et al., 1993), sorting and weighing the waste materials on site (Bossink and Brouwers, 1996), collecting data through consultation with construction company employees (Tam et al., 2007a; Treloar et al., 2003), and tape measurement and truck load records (Poon et al., 2001a, 2004a). Two approaches currently prevail for measuring WGR: classifying wastes into different categories, and treating them as a whole. After Skoyles (1976) examined WGR related to 37 materials individually, many later studies (e.g. Tam et al., 2007a; Formoso et al., 2002, Treloar et al., 2002; Bossink and Brouwers, 1996) followed the approach by investigating WGR by differentiating material waste such as steel, cement, concrete, mortar, timber, and so on. Other studies (e.g. Poon et al., 2004a) treated the waste as a whole and derived a general rate of waste, such as volume (m^3) or quantity (tons), per m^2 of GFA.

While the total volume of C&D waste in a particular region or country is useful as well as informative for understanding the status quo of C&D waste, the C&D WGR, from a different angle, enables the examination and comparison of different levels of waste generation. Considering the volumes of annual C&D waste generation of various economies differ largely depending on a wide range of factors, including economy development, population, territory and demand for construction and demolition, C&D WGR offers a platform for comparing waste management practices of different projects, regions and countries. It also provides an effective way to assess the performance of waste management because it usually allows areas of potential to be pointed out and main causes of inefficiency to be identified (Formoso et al., 2002). By measuring C&D waste management performance based on WGR, different C&D waste management practices can be benchmarked and effective strategies for waste management can be developed.

The two approaches for measuring WGR serve different purposes. When treating all waste as a whole, the WGR helps to identify the total amount of waste generated from a project or multiple projects. When classifying waste into different categories, it helps to identify waste according to its properties by looking into its causes (e.g. building technologies, material handling process, waste treatment). It is considered the WGR is more effective than the measurement of total amount of C&D waste when comparing different waste generation practices.

2.4 Strategies for C&D waste management

C&D waste management research and practices have been guided by a '3Rs' principle, which is also known as the hierarchy of C&D waste management (see Figure 2.1). The principle refers to the 3Rs of reduction, reuse and recycling, which classify waste management strategies according to their desirability (Peng et al., 1997). The 3Rs is meant to be a hierarchy, arranged in ascending order of their adverse impacts to the environment from low to high.

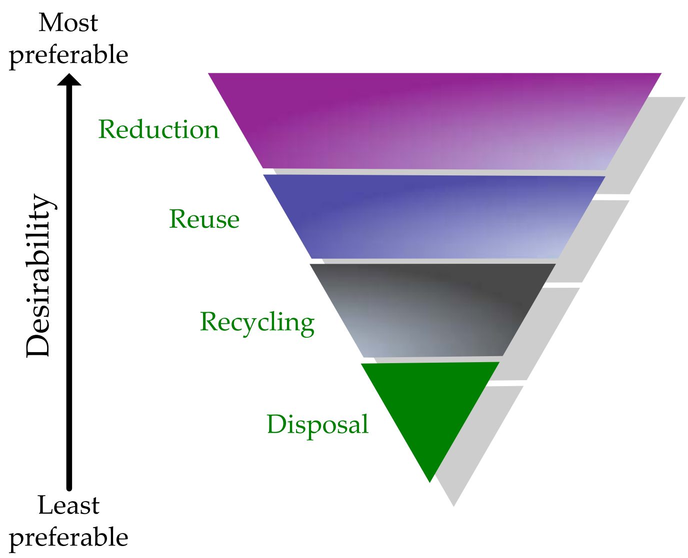

Figure 2.1: Hierarchy of C&D waste management

2.4.1 C&D waste reduction

Reduction is considered as the most effective and efficient method for managing C&D waste. It can not only minimize the generation of C&D waste, but also cut the cost for waste transporting, recycling and disposal (Poon, 2007; Esin and Cosgun, 2007). As the highest priority for managing C&D waste, it is not surprising to see that C&D waste reduction has been examined extensively by previous researchers.

Various approaches have been employed by studies pertaining to C&D waste reduction, including survey, case study, descriptive models, and deployment of mathematical models and information technology. Site observations, questionnaires and interviews are the main survey methods and are particularly useful when the aim is to study causes of C&D waste and factors either hindering or contributing to the successful implementation of C&D waste reduction, investigate the wastage level of various trades, or elicit views of major stakeholders on C&D waste reduction (Begum et al, 2007b; Baldwin et al., 2007; Poon et al., 2004b, 2004c; Faniran and Caban, 1998). Case study serves a similar purpose as survey method (Poon et al., 2004c; Seydel et al., 2002), but results from limited cases are not reliable and cannot therefore be applied to other projects. The waste flow process can be depicted by descriptive models (e.g. Lu et al., 2006; Shen et al., 2004). By mapping the waste handling processes, different waste management practices can be presented as a tool to assist in planning on-site waste management procedures and enable the comparison of different waste management practices. This helps to identify both good practices and weak areas in C&D waste management (Shen et al., 2004). With the aid of mathematical models and information technology, the waste handling process can be optimized (Lu et al., 2006), workers can be motivated to reduce waste (Li et al., 2005; Chen et al., 2002), and a better understanding of the dynamic interactions of key areas of the C&D waste management process can be facilitated (Hao et al., 2007b). In summary, the survey and descriptive models are helpful in acquiring a qualitative understanding of C&D waste reduction, while the case study and mathematical models are useful for quantitatively improving the performance of C&D waste management.

The measures for effectively reducing C&D waste can be summarized into five categories: (1) reducing waste through governmental legislations, (2) reducing waste by project design, (3) developing an effective waste management system (WMS), (4) adoption of low-waste construction technologies, and (5) improving major stakeholders' attitudes toward waste reduction.

The effectiveness of legislation for reducing C&D waste has attracted significant attention. For example, the effectiveness of implementing a waste management plan proposed by the Hong Kong government was investigated by Tam (2008a), and Hao et al. (2008a) conducted a study on the effectiveness of Hong Kong's Construction Waste Disposal Charging Scheme. The results showed that C&D waste was reduced by approximately 60% in landfills, by approximately 23% in public fills, and by approximately 65% in total waste generation between 2005 and 2006. This, to a large extent, demonstrated that governmental legislation has an important role to play in C&D waste reduction.

Solutions arising from project design are also important, since waste caused by design changes has been found to be the most significant source of C&D waste (Osmani et al., 2008; Faniran and Caban, 1998). According to the principal findings of a survey in Singapore, four out of eight critical sources of site waste are from project design (Ekanayake and Ofori, 2004). Studies by Baldwin et al. (2007; 2008) showed how modeling information flows in the design process might be used to evaluate design solution for reducing waste in high-rise residential buildings.

Impressive results can be achieved by putting emphasis on developing an effective WMS for construction projects (McGrath, 2001). In a sense, development of a WMS is a holistic strategy for minimizing waste generation in the construction process (McDonald and Smithers, 1998). A WMS generally comprises five key elements: (1) waste management policy, (2) planning, (3) implementation and operation, (4) checking and corrective action, and (5) management review. As the key component of a WMS, the importance of a waste management plan (WMP) has been highly emphasized by some studies (e.g. Poon et al., 2001b). A WMP contains a set of waste prevention strategies involving the effective coordination of material management, the use of materials to minimize loss, maximizing reuse, preventing undoing and redoing, and reducing packaging waste (Chen et al., 2002). It is considered proper to evaluate the effectiveness of a WMP from a perspective of integrating society, the environment and the economy. However, how to develop a scheme which is economically competitive has attracted the most attention from researchers (Begum et al., 2006; Chen et al., 2002; Mills, 1999). This is probably because major stakeholders are more likely to be motivated if they are rewarded according to the amounts and values of materials saved (Li et al., 2005; Chen et al., 2002). In addition, cost is commonly a much higher priority than the environment amongst the objectives of construction projects (Shen et al., 2006).

Previous studies have recognized the potential of low-waste construction technologies, such as prefabrication and modular structure in buildings, for minimizing C&D waste (Jaillon et al., 2009; Jaillon and Poon, 2008; Esin and Cosgun, 2007; Tam et al., 2007b; Poon et al., 2004a). Baldwin et al. (2007, 2008) argued that for high-rise residential buildings, the main opportunities for waste minimization are related to the adoption of pre-fabrication techniques, while Jaillon et al. (2009) suggested that waste reduction is one of the major advantages of using prefabrication. This was supported by a finding from Tam et al. (2007b) that adoption of prefabrication in concreting could achieve a 90% waste reduction compared with cast-in-situ. The implication of the foregoing is that a wider use of low-waste construction technologies could considerably reduce C&D waste.

Recognition by major stakeholders of the need to reduce waste has also been perceived as an effective solution to C&D waste reduction. Lingard et al. (2000) revealed the understanding of both managers and site workers of the need for waste reduction, while the attitudes of site workers toward waste management were investigated by Teo and Loosemore (2001) and Chen et al. (2002) and Osmani et al. (2006) conducted a study in the UK to assess architects' views on the origins of design waste, as well as barriers to waste reduction. Findings of these studies suggest that it is crucial to take the attitudes of major stakeholders into account when exploring possible solutions to C&D waste reduction. The findings also indicate that attitudes toward C&D waste reduction differ between various groups of stakeholders.

The discussions above testify to the fact that measures for C&D waste reduction are well developed. Nevertheless, how to apply them effectively to different practices remains a challenge. Tam et al.'s (2008a) investigation showed that schemes from the Hong Kong government have been criticized by industry participants because the productivity of these schemes is largely affected when implemented in practice. Similarly, despite the consensus in the literature that C&D waste can be greatly reduced by focusing on design waste, findings from Osmani et al. (2006) revealed that waste management is not a priority in the design process and that architects typically hold the view that waste is mainly produced by site operations. Another study on architects' attitudes toward waste management showed that they are reluctant to adopt waste reduction strategies at the design stage (Osmani et al., 2008), probably because of the belief that C&D waste management is out of their control and is not cost-effective (Lingard et al., 2000). Furthermore, Tam et al. (2007b) identified drawbacks of prefabrication, including inflexibility for design changes and higher initial construction cost. This was supported by Jaillon et al. (2009), who identified key obstacles to a wider use of prefabrication in residential buildings that included the need for specification change, conflict with traditional design process, lack of incentives, lack of on-site cast yard areas, and conflict with construction practice.

2.4.2 C&D waste reuse and recycling

Reuse means using the same material more than once. This might be for the same function, such as formwork (Ling and Leo, 2000) or for a new function, such as using cut-corner steel bar for shelving (Duran et al., 2006). The waste materials that cannot be reused will either be recycled for new construction use or disposed of at landfills. Reuse is therefore the most desirable option after reduction because of the minimum processing and energy involved (Peng et al, 1997). When reduction and reuse become difficult, recycling is the next best option. Through recycling, some new materials can be made out of the C&D waste. Tam (2008a) and Kartam et al. (2004) suggested that recycling could offer five major benefits: (1) reducing the demand for new resources, (2) cutting down transport and energy production cost, (3) utilizing waste that would otherwise be lost to landfill sites, (4) preserving areas of land for future urban development, and (5) improving the quality of the environment.

By comparison with reduction and recycling, relatively fewer studies have been conducted on reuse of C&D waste.. A study by Ling and Leo (2000) found that there are three sub-factors of most importance affecting the reuse of timber formwork, namely, the workers' attitudes, the workers' efficiency, and formwork stripping process It is reasonable to conclude that effective solutions to waste reuse depend highly on the stakeholders involved, rather than the wasted material itself.

On the other hand, waste recycling is attracting considerable attention. A study by Lauritzen (1998) showed that recycled materials would normally be competitive where there is a shortage of both raw materials and suitable deposit sites. Additionally, two determinants for using recycled materials in construction projects exist. One determinant is transportation facilities, such as roadways, railways and pipelines. Since virgin materials usually have to be transported from distant sources, it might be more cost efficient to use recycled materials in close proximity. The other determinant is high population density, particularly for countries and regions with large populations and scare space for disposal (Inyang, 2003). These determinants are supported by the findings of Peng et al. (1997) and Tam and Tam (2006a), both of whom concluded that from a purely economic point of view, recycled materials are only attractive when they are competitive with virgin materials in terms of cost and quality. Clearly then, cost and quality are the major considerations when adopting recycled materials.

A number of studies have been launched to deal with the two major concerns over waste recycling: the economic viability and acceptability of recycled materials (e.g. Tam, 2008b; Rao et al., 2007; Tam and Tam, 2006b; Bianchini et al., 2005). Studies have also evaluated the financial feasibility of investing in recycling centers with Nunes et al. (2007) showing that recycling centers could be economically viable for public authorities providing there is continuity and sufficient production volume.

2.4.3 C&D waste disposal

In accordance with the hierarchy of C&D waste management as shown in Figure 2.1, when C&D waste cannot be effectively minimized based on the 3Rs principle, it should be disposed of at landfills and/or public fills to avoid polluting the environment. However, uncontrolled and illegal dumpling of C&D waste has been widely occurring in many economies (Zygouras et al., 2009; Esin and Cosgun, 2007). Generally, there are two ways to reduce uncontrolled and illegal dumping: one is by polluters' (such as contractors, sub-contractors and waste contractors) willingness to dispose of waste at landfills and the other is through government regulations (Hao et al., 2008a; Tam et al., 2007a). Unfortunately, studies indicate that voluntarily disposing of C&D waste at landfills and/or public fills does not work effectively in many economies. The major barrier is that polluters will spend extra costs for waste disposal under the polluters-pay-principle (Begum et al., 2007a). This to some extent implies that the reduction of illegal dumplings can only be effective by regulating the disposal behavior, and these regulations must be enforced by the Government..

Although many countries/regions have legislation aimed at regulating C&D waste disposal, the outcomes are far from effective (Kofoworola and Gheewala, 2009; Tam, 2008a; Wang et al., 2008). How to effectively implement legislation related to C&D waste is the subject of much research. For example, through a questionnaire survey Tam et al. (2007c) found that the reason for the limited effectiveness of regulatory measures in Hong Kong is that these measures allow for skewed distribution of commitments and responsibilities among key project participants.

A major focus of studies relating to regulatory measures for C&D waste management is the waste charging scheme (WCS). WCS imposes a levy on those who dispose of their C&D waste into public landfills. Therefore it is also called a landfill charging scheme or waste disposal charging scheme. The scheme is not only intended to provide an economic incentive for key stakeholders to reduce waste but also to encourage reuse and recycling of wasted material in order to slow down the depletion of limited landfill and public fill capacities (Hao et al., 2008a).

To deal with the challenge of limited landfills for C&D waste, the cost for disposing of C&D waste has increased significantly worldwide (Peng et al., 1997). For instance, in Southeast Queensland, Australia, a levy reflecting the environmental and social costs of landfilling was imposed to encourage the diversion of waste from landfills (Tam et al., 2009). In Hong Kong, a charge for C&D waste disposal, initially at HK$55/t (US$7/t), has been increased to HK$120/t (US$15.2/t) and is thought to have reduced the amount of inert C&D waste entering landfills (Poon et al., 2001b).

Measures to improve the effectiveness of WCS have also been developed in previous studies. Based on daily C&D waste records from landfills and public fill facilities, Hao et al. (2008a) found that C&D waste dumped at landfills and public fills was reduced by approximately 65% after implementing a WCS. This can lead to further improvement in reducing waste by embodying WCS to waste reduction guidelines, providing thresholds for the amount of waste sent to landfills or public fills, using waste dumping charge as an incentive, encouraging the recycling of different type of C&D waste, and promoting the use of recycled materials.

Waste disposal charges are an important component of WCS and greatly influence the effectiveness of implementing a WCS in a given country. The majority of studies tend to suggest that disposal charge should be higher than they already are. However, an overly-high waste disposal charge might alienate major stakeholders, such as clients and contractors, and thereby lose their active participation and support. Economists give waste disposal charges a theoretical explanation: the low cost of C&D waste dumping generally leads polluters (C&D waste producers) to dispose of most of their waste in landfills, where society has to incur the environmental cost. By using a WCS, policy makers are attempting to internalize the costs by ensuring that the polluters themselves and not society incur the costs (Craighill and Powell, 1999). In order for WCS to be effective, the charge should be such that it encourages the joint efforts of major stakeholders to reduce the amount of C&D waste entering landfills, rather than simply a way of imposing economic measures against the polluters.

2.5 Stakeholders' attitudes toward C&D waste management

Attitude refers to a positive or negative feeling toward specific objects; it exerts an influence on behavior (Begum et al., 2009). Ever since some studies suggested that changing project stakeholders' wasteful behavior could contribute significantly to the effectiveness of C&D waste management (Lingard et al., 2000; Teo and Loosemore, 2001), there have been attempts by other researchers to discover ways of changing project stakeholders' attitudes toward C&D waste management.

These studies have mainly concerned with three groups of project stakeholders, namely, architects, contractors, and workers. Focusing on architects' attitudes toward waste reduction, the findings of Osmani et al. (2008) suggested that waste management is not a priority in design, since architects generally perceive that C&D waste is mainly produced by site activities and rarely have anything to do with project design, even though research by Saunders and Wynn (2004) showed that poor project design results in excessive off-cuts and is a major cause of wastage on construction sites.

Saunders and Wynn (2004) revealed that although there is willingness for labor only sub-contractor to budget for some of the costs for managing C&D waste, it would be more sustainable if there is an equitable sharing of benefits arising from the treatment of C&D waste management. In a sense, the sharing of benefits is critical for affecting stakeholders' attitudes toward C&D waste management. Begum et al. (2009) identified factors significantly affecting contractors' attitudes towards waste management, including contractor size, source reduction, reuse and recycling measures, frequency of waste collection, staff participation in training programs, and waste disposal methods; more particularly, they found that contractors' attitudes and behavior regarding C&D waste management tended to differ according to their size.

By using 'Ajzen's theory of planned behavior', Teo and Loosemore (2001) investigated the attitudinal forces that shape the behavior of construction workers. It was found that workers tend to perceive C&D waste management as unimportant if there are no necessary supporting facilities, incentives and resources provided by project managers. Similar findings have also been disclosed by Lingard et al. (2000), who claimed that the availability of local infrastructure and top management support are the two most important issues perceived by construction workers. These findings demonstrate clearly that resources out of workers' control are the main determinants for them to change their attitudes toward C&D waste management.

Despite the diverse factors revealed by different researchers, there seems a consensus that training programs are effective for promoting stakeholders' awareness and improving their attitudes toward C&D waste management. Training programs for cultivating a waste collection and minimization culture among workers are considered important in driving their motivation to minimize C&D waste (McDonald and Smithers, 1998). Tam et al. (2005) noted that proper training and education are strongly needed within the construction industry to facilitate the successful implementation of prefabrication. Furthermore, Begum et al. (2009) demonstrated that contractors with staff who have participated in C&D waste management training programs have a more positive attitude toward waste management when compared to contractors with staff who have not participated in such training programs.

2.6 Approaches adopted for assessing C&D waste management

An extensive search of relevant literature revealed that wide-ranging approaches have been introduced and applied to the practice of evaluating C&D waste management. Their assessment is focused on a particular aspect such as economic performance, environmental performance, or social performance. The following section provides a brief review of these approaches.

<u>Approaches for assessing the economic performance of C&D waste management</u>

As discussed above, there is substantial evidence demonstrating that implementing the 3Rs strategies in practice is not as effective as anticipated. One major factor hindering the effectiveness of C&D waste management activities is a lack of economic incentives (Yuan et al., 2010). In other words, whether they can get economic benefits from managing C&D waste management is the stakeholders main concern and environmentally friendly practice is not high on their agenda (Lu and Yuan, 2010; Shen et al., 2006). Therefore, it is not surprising that assessing economic performance of C&D waste management is dominant among all studies associated with the discipline.

The term ‘economic performance assessment’ concerns the evaluation of the costs and profits of a specific activity and is very useful for understanding the costs and benefits of all activities relating to C&D waste over the whole lifecycle of construction projects. Hence, approaches used for assessing the economic performance of C&D waste management mostly concentrate on the cost-benefit analysis of related activities.

The economic benefits of waste minimization and recycling are enormous. They typically include the sale of specific waste material and the removal from site of other waste at no charge or reduced cost, with a subsequent reduction of charges for material that has to go to landfill (Snook et al., 1995). On one hand this favors construction companies by reducing their costs (Guthrie et al., 1999) and improving their competitiveness through lower production costs and a better public image (Begum et al., 2006), while on the other hand, it encourages reuse and recycling of waste materials thereby slowing down the depletion of landfill capacities (Hao et al., 2008b). However, there are costs involved for waste collection, separation and sorting, waste reuse, recycling, and waste disposal (Yuan et al., 2010). Throughout the lifecycle of construction projects, the counterpoise between benefits and costs associated with C&D waste management is dynamic and uncertain.

Previous studies under the umbrella of assessing the economic performance of C&D waste management have mainly been carried out through cost-benefit analysis. For example, based on pertinent economic factors such as transportation, labor, and disposal costs, Mills et al. (1999) developed a model that allowed for choosing the most cost-effective work management plan (WMP); the costs and benefits of a WMP were calculated based on results of an analysis of all costs and benefits appertaining to executing the WMP and the equations were organized in a spreadsheet format with the aid of Microsoft Excel. Another study, by Begum et al. (2006), used cost-benefit analysis to investigate the feasibility of waste minimization through the employment of several mathematical equations and by dividing costs and benefits of C&D waste management activities into different sub-categories; the researchers claimed that their model provides a profile of exhibiting the amount of waste generation, sources and compositions as well as reuse and recycling of materials on construction sites taking into account the economic dimension. In addition, a model was developed by Duran et al. (2006) for assessing the economic viability of creating markets for recycled C&D waste under different economical instrument scenarios; particular emphasis was given to the assessment of impacts of environmental taxes and the use of subsidies on the economics of C&D waste recycling. More recently, Tam (2008b) investigated the economics of recycling concrete waste by comparing the costs and benefits of traditional practice with the recycling method; the conclusion was that recycling concrete waste for new production was cost-effective. Furthermore, a practical guide on cost-benefit analysis specifically for solid waste management was released by Nordic Council of Ministers (Skovgaaed et al., 2007).

Approaches for assessing environmental performance of C&D waste management

Assessing environmental performance is a process by which information about the likely effects of implementing C&D waste management on the environment is evaluated. Typical approaches adopted for assessing environmental performance of C&D waste management include environmental impact assessment (EIA), strategic environmental assessment (SEA) and lifecycle assessment (LCA).

EIA is an assessment of the possible positive and negative impacts that C&D waste management activities may have on the environment (Wikipedia, 2011). It will involve a number of procedures. For example, to assess the environmental impact of recycled material in a road structure during the service life of the road, eight steps would be followed, namely, defining the problem, describing the scenario, describing the waste (the recycled material), determining the influence parameters on leaching, modeling leaching behavior, validating behavioral model, concluding, and assessing risk (Petkovic et al., 2004). Normally, EIA is used to assess and compare environmental impacts of different waste management schemes, so that the scheme with the lowest impact on the environment could be identified (Emmanuel, 2004; Trankler et al., 1996).

SEA is a more recently introduced method intended to be used at an earlier stage in the decision-making process, on a more strategic level (Finnveden et al., 2007). Therefore, it would be more appropriate to use SEA as a tool for estimating the environmental impact of a specific waste management solution before implementing it. For example, it was adopted by Kartam et al. (2004) to identify the potential environmental problems of C&D waste management in Kuwait. Alternative solutions to manage C&D waste in an environmentally safe manner were investigated in the same study.

LCA is a method to assess the environmental impacts and resources used throughout the entire C&D waste management process from raw material acquisition through to production, use and disposal (Finnveden et al., 2007). It is a well established method for providing waste planners and decision-makers with a framework to evaluate waste management measures (Obersteiner et al., 2007). According to Birgisdottir (2004), LCA makes it possible to take into account the significant environmental benefits that can be obtained through different waste management processes. An LCA is generally performed following four steps: defining the goal and scope, analyzing inventory, assessing the lifecycle impacts, and interpreting the findings (ISO, 2006). Following this typical procedure, Ortiz et al. (2010) carried out a study for evaluating environmental impacts of C&D waste management through comparing landfilling, recycling, and incineration scenarios. Findings from the study provide decision-makers with a better understanding of the environmental impact of different waste management measures.

Approaches for assessing social performance of C&D waste management

The International Association for Impact Assessment (IAIA) provides a definition for social impact assessment, namely, “it includes the processes of analyzing, monitoring and managing the intended and unintended social consequences, both positive and negative, of planned interventions (policies, programs, plans, projects) and any social change processes invoked by those interventions. Its primary purpose is to bring about a more sustainable and equitable biophysical and human environment.” (IAIA, 2011).

Compared to research on economic performance and environmental performance assessment previously discussed, research on assessing social performance of C&D waste management receives much less attention. A study by Klang et al. (2003) proposed a model for evaluating the environmental, economic and social sustainability of demolition waste. By inputting data obtained from a practical case into the established model, social impacts of demolition waste were studied. The authors found the data collection needed to perform this kind of analysis resource-demanding and suggested that it would be better to identify a limited number of key indicators on environmental, economic and social performance. Recently, Rocha and Sattler (2009) examined the major economic and legal factors influencing the reuse of C&D waste in Brazil through a case study, and analyzed the social influence from a qualitative point of view.

There are probably three reasons for the scant research into SIA. Firstly, the social influence of performing C&D waste management is by and large of lower priority when implementing construction projects. In most cases, the major focus will be given to project objectives such as cost, time, duration, and safety (Shen et al., 2006). Secondly, social performance is not always amenable to empirical measurement (Dale et al., 1997). Fundamentally, many indicators used for SIA are qualitative and are very difficult to be quantified. Finally, implementing C&D waste management affects different groups of project stakeholders in different ways. Major stakeholders involved in C&D waste management can be generally divided into two groups: one group includes the authorities, general public and NGOs; the other major group comprises project clients, main and subcontractors (Yuan and Shen, 2011). The former group tends to be concerned more about minimizing the amount of C&D waste entering landfills and generally lessening the environmental and social impacts, while the latter group is concerned more with the economic benefits that can be derived from managing C&D waste and are less concerned with whether or not the waste would be a burden on the environment or society. The latter group is more powerful in developing and executing C&D waste management plans, particularly in developing economies. This explains why more emphasis has been placed on the assessment and monitoring of economic performance in the process of C&D waste management.

2.7 Limitations of existing research

It is clear from the foregoing critical review of relevant literature that a significant body of research has been dedicated to a broad range of topics in the discipline of C&D waste management over the last few decades. The outcomes have not only greatly enriched the body of knowledge of C&D waste management, but also provided useful information about C&D waste management practices worldwide.

However, one of the gaps in the literature is an insufficiency of research into how to better assess the effectiveness of a C&D waste management system by considering collectively its economic performance, environmental performance and social performance. This research gap is evidenced by the following:

- *Processes of C&D waste management have been treated separately.* Current measures for dealing with C&D waste are guided by the waste management hierarchy, which arranges waste management processes, such as C&D waste generation, reduction, reuse, recycling, and disposal, in a series. In line with the hierarchy, research has largely addressed C&D waste related problems that arise from a specific waste management process.

- *Elements in different C&D waste management processes are considered as* *independent.* In conventional C&D waste management approaches, processes including waste generation, reduction, recycling, and disposal are viewed as independent operations (Seadon, 2010). However, as argued by Hao et al. (2010), many of the elements are interdependent. For example, design changes occurring at the project design stage could lead to generation of C&D waste at the construction stage (Osmani et al., 2006, 2008), and waste disposal fees can also affect the implementation of C&D waste management strategies on construction sites (Hao et al., 2008b). Failure to consider such interrelationships is probably one reason why there is an insufficient understanding of the effectiveness of C&D waste management (Hao et al., 2010).

- *Most studies have been carried out from a static point of view.* Measures presented for coping with C&D waste management problems have by and large been based on empirical results obtained from surveys and do not show how C&D waste management problems vary across the waste management process. Approaches previously employed for assessing C&D waste management have only assessed results on completion of construction projects and failed to assess the impacts of C&D waste management activities from a dynamics perspective.

- *Very few studies have been dedicated to evaluating C&D waste management* *by integrating economic performance, environmental performance and social performance as a whole*. While a significant number of studies have focused on the economic performance of C&D waste management, very few studies have assessed the social performance of C&D waste management. However, in line with the principle of sustainable development (WCED, 1987), effective C&D waste management should embrace the notion that economic performance, environmental performance, and social performance of C&D waste management are harmoniously emphasized and promoted in managing C&D waste.

In view of the limitations of existing research presented above, further research should address the following points:

- *C&D waste management is a complicated system.* The C&D waste management is a complicated system can be demonstrated by the number of elements involved; waste generation, reduction, reuse, recycling, and disposal, are all parts of the system. In addition, each of the C&D waste management activities involves different stakeholders (Yuan and Shen, 2011). An interdisciplinary approach involving all elements is therefore necessary to ensure that the C&D waste management system can be fully understood (Graham and Smithers, 1996).

- *Elements within the C&D waste management systems are largely* *interdependent.* A conventional C&D waste management approach treats waste generation, reduction, recycling and disposal as independent operations. However, all of them are closely interlinked and each one influences the other (Seadon, 2010). Hence, effective C&D waste management should take into account the interrelationships of different operations (Clark, 1978).

- *C&D waste management systems are dynamic*. Conventional C&D waste management research mostly tends to view C&D waste management from a static point of view, failing to have an understanding of the dynamics of the system (Yuan et al., 2010).

- *The three dimensions of C&D waste management, namely, economic performance, environmental performance, and social performance, should be holistically considered when understanding and assessing the effectiveness of C&D waste management.*

By taking account of the forgoing four points, the research question for this study was established as: ‘Is it possible to holistically assess and improve the effectiveness of a C&D waste management system by considering the dynamic interrelationships of the major variables within the system?’.

2.8 A path forward

As shown in Section 2.7, the systematic approach offered by system dynamics (SD) is capable of dealing with the four limitations discussed above.

Firstly, SD is designed for dealing with systems of complexity. Complexity refers to a high-order, multiple-loop, non-linear feedback structure to which all social systems belong. There is a widely accepted view that SD is superior to other approaches for dealing with problems of high complexity (Maani and Mahara, 2004). It has been pointed above that the management of C&D waste is a complex system due to the interrelationships of the numerous elements involved (Hao et al., 2007b).

Secondly, with a SD approach, the interrelated connections underlying major elements involved in C&D waste management systems can be better depicted and modeled. This is supported by a number of studies conducted in the past few decades that have applied the SD approach to political, economic, managerial, and environmental systems (Lin et al., 2008; Wolstenholme et al., 2007; Dyson and Chang, 2005; Sterman, 1992; Forrester, 1961, 1994). In terms of environmental concerns, the application has covered several issues, including salt accumulation in lowlands under continuous irrigation practice (Saysel and Barlas, 2001), value of water conservation (Stave, 2003), the eutrophication problem in shallow freshwater lakes (Guneralp and Barlas, 2003), the impact of environmental issues on long-term behavior of a single product supply chain with product recovery (Georgiadis and Vlachos, 2004), sustainability of ecological agricultural development at a county level (Shi and Gill, 2005), and waste management (Karavezyris, 2007; Dyson and Chang, 2005). These studies show that SD provides a common foundation that can be applied to facilitate an understanding of the relationship between the behavior of a system over time and its underlying structure and decision rules (Wolstenholme, 1990).

Thirdly, a SD approach enables the presence of changes in system behavior over time. As indicated by its name, SD has the merit of modeling the dynamic behavior of a system. Sterman (1992) concluded that SD is an effective analytical tool for understanding the dynamics of construction projects, and Hao et al. (2007b) developed a SD-based model for strategic planning of C&D waste in Hong Kong paying particular attention to the complexity of information and processes involved in managing C&D waste throughout the lifecycle of construction projects.

Fourthly and finally, an assessment of the effectiveness of C&D waste management should include the effects of waste management activities from the economic performance, social performance, and environmental performance perspectives. Shen et al. (2005) developed a simulation model for assessing the sustainable performance of projects, in terms of their economic, environmental and social sustainability. The study argued that a SD approach was capable of simultaneously dealing with the three aspects while assessing the sustainable performance of construction projects. In light of that study, it was reasonable to assume that by using a SD approach it would be possible to assess effective C&D waste management by abstracting and modeling economic performance, environmental performance, and social performance through three interconnected subsystems.

Based on the above discussion, it was concluded that an SD approach would be an appropriate method for dynamically assessing the effectiveness of C&D waste management systems and was therefore adopted for this study.

2.9 Summary

This chapter provided a comprehensive review of the literature related to C&D waste management. The wide spectrum of topics involved were summarized into five major groups, namely, definition of C&D waste, C&D waste generation, strategies for C&D waste management, stakeholders' attitudes toward C&D waste management, and approaches for assessing C&D waste management. The review provided a general picture of the status quo of C&D waste management research.

Based on perceived gaps in the literature, the question of whether it is possible to holistically assess and improve the effectiveness of a complicated C&D waste management system by considering the dynamic interrelationships of its variables, was developed as the overarching research question for this study.

The next chapter identifies major variables affecting the effectiveness of C&D waste management. The variables are mainly related to three dimensions in evaluating the effectiveness of C&D waste management, namely, economic performance, environmental performance, and social performance. The identification of major variables will serve as a basis for development of a dynamic model.

CHAPTER 3 Major Variables Affecting the Effectiveness of C&D Waste Management

3.1 Introduction

The purpose of this chapter is to explain how the major variables that affect the effectiveness of C&D waste management systems were formulated. The meaning of the term 'effectiveness of C&D waste management' is explored and the definition as used in this study is provided. Then the three aspects associated with implementing C&D waste management, namely, economic performance, environmental performance, and social performance, are reviewed and discussed in order to lay the foundation for identification of the major variables affecting the effectiveness of C&D waste management systems. Finally, an explanation is provided as to how those variables were incorporated into a two-tier hierarchy system for evaluating the effectiveness of C&D waste management.

3.2 Effectiveness of C&D waste management

While acknowledging its significant contribution to the development of society, the construction industry has also been perceived as a major contributor to environment degradation worldwide (Poon et al., 2004b; Bossink and Brouwers, 1996). Its negative impacts include, *inter alia*, land depletion and deterioration, energy consumption, solid waste generation, dust and gas emission, noise pollution, and consumption of non-renewable natural resources (Shen et al., 2007; Sjostrom and Bakens, 1999; Ofori, 1992). C&D waste has therefore been one of the major pollutants caused by construction activities.

Since the early 1980s, with the increasing recognition of sustainable development as an important value (WCED, 1987), a diversity of industries including the construction sector have been taking actions to promote both research and practice in each of the sectors for embracing sustainable development principles. However, the literature to date determines that when performing C&D waste management, economic performance is still the foremost objective while environmental and social performance are of lower priority (Wang et al., 2010). This contrasts sharply with the principle of sustainable construction, which is defined as "a holistic process aiming to restore and maintain harmony between the natural and the built environment, and create settlements that affirm human dignity and encourage economic equity." (Du Plessis, 2002). Since effective C&D waste management is one integral process for the attainment of sustainable construction, it should not only emphasize the economic performance, but also highlight associated social and environmental performance. Therefore, *effectiveness of C&D waste management* for this study was defined as:

> The degree to which objectives are achieved when implementing C&D waste management; where the objectives mainly concern how to simultaneously promote the economic, environmental and social performance of C&D waste management activities in the project.

Meaning of 'effective C&D waste management' can be further expatiated through a three-sphere diagram, as illustrated in Figure 3.1.

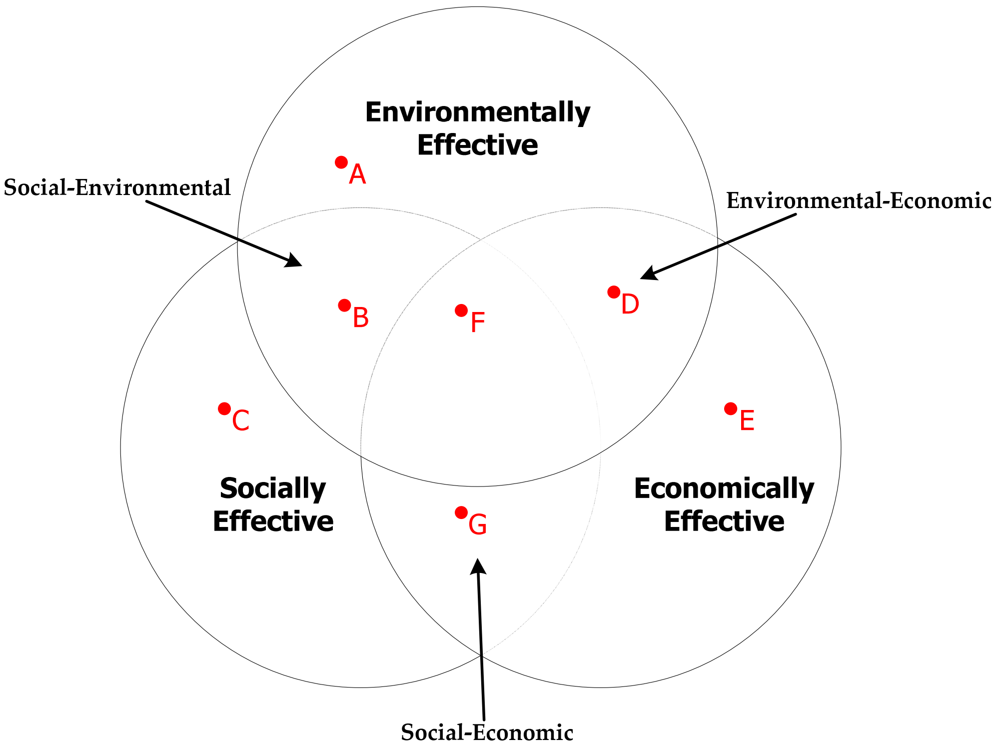

Figure 3.1: Three spheres of effective C&D waste management

In the above Figure, the three spheres represent the economic, environmental and social performance of C&D waste management respectively. As discussed above, effective C&D waste management should holistically maintain the harmony development of these three aspects. Failure to promote any of the aspects when implementing C&D waste management would affect its overall effectiveness, which is clearly demonstrated by areas of A, B, C, D, E and G in Figure 3.1. Therefore, only those construction projects that fall in area F can be perceived as satisfactorily effective in terms of C&D waste management.

Based on the above analysis, major variables that influence the effectiveness of C&D waste management can be identified from three aspects accordingly, i.e. economic, environmental, and social performance. In fact, understanding C&D waste generation forms the basis of evaluating the economic, environmental and social performance of waste management activities. Therefore, the identification of principal variables affecting C&D waste generation is also important, which is addressed in the next section.

3.3 Variables affecting C&D waste generation

A review of the literature indicates that major variables influencing C&D waste generation can be broadly grouped under seven headings, encompassing design changes, investment in C&D waste management, C&D waste management regulations, site space for performing waste management, adoption of low-waste construction technologies, impacts of waste reduction cost, and waste management culture within an organization. These variables and the literature where each of the variables were derived are tabulated in Table 3.1.

Table 3.1: Major variables affecting C&D waste generation

No.	Variables	Sources
1	Design changes	Faniran and Caban (1998); Poon et al. (2004b); Ekanayake and Ofori (2004); Osmani et al. (2006).

2	Investment in C&D waste management	Chen et al. (2002); Osmani et al. (2006); Kulatunga et al. (2006); Begum et al. (2007b).
3	C&D waste management regulations	Hadjieva-Zaharieva et al. (2003); Saunders and Wynn (2004); Clark et al. (2006); Osmani et al. (2006); Kulatunga et al. (2006); Kofoworola and Gheewala (2009).
4	Site space for performing waste management	Poon et al. (2001b); Chen et al. (2002); Wang et al. (2010).
5	Adoption of low-waste construction technologies	McDonald and Smithers (1998); Hao et al. (2008b); Tam (2008a).
6	Impacts of waste reduction cost	Mills et al. (1999); Poon et al. (2003); Saunders and Wynn (2004); Kulatunga et al. (2006).
7	Waste management culture within an organization	Treloar et al. (2003); Begum et al. (2007b); Tam (2008a).

Design changes

There is a general consensus among previous studies that design changes occurring during construction is one of the most significant sources engendering the huge amount of C&D waste (Ekanayake and Ofori, 2004; Faniran and Caban, 1998). Particularly, Osmani et al.'s (2008) study estimated that approximately 33% of on-site waste is related directly or indirectly to project design. Also, an earlier study by Osmani et al. (2006) revealed that C&D waste management is not put to a priority in the stage of project design.

Changes to the original design can normally cause waste in two ways (Faniran and Caban, 1998). Firstly, if construction materials have already been purchased in line with the original design, C&D waste could be caused if the materials cannot be resold or returned to the supplier, and the only option is to dispose of them. Secondly, if a structure has already been constructed, any change in the design might result in part of the structure being taken apart; in such a situation, waste results if the materials cannot be salvaged. The process of waste generation through project design is complex due to the usage of a diverse of materials and the involvement of other project stakeholders besides designers, such as clients and contractors (Keys et al., 2000) [cited in Osmani et al. (2008)]. Such complexity consequently results in that very few attempts are being made to minimize waste during project design (Osmani et al., 2006). This is probably the underlying as well as a key barrier to the effective operation of waste minimization in the stage of project design.

Further understanding on waste generation variables can be gained by referring to the Chinese construction practice. For example, construction practice in Shenzhen indicates that in order to meet the requirements of high-speed development of the city, the design of a construction project is hastily implemented without sufficient time to scrutinize the design closely. According to Zhu (2009), this practice can be traced back to the 1950s when the People's Republic of China (PRC) was founded and the Top Ten Beijing Buildings program was launched; even the design of the Great Hall of the People had not been completed when construction commenced. Lu and Yuan (2010) further revealed that another reason for too many design changes in construction is that clients usually fail to conduct a sufficiently thorough market analysis before investing in a project. A quick design and insufficient market investigation often lead to design changes during the construction process, which in turn leads to cost overruns and more C&D waste. Their study also suggested that better project design management can be a solution to effective C&D waste minimization. Therefore, it can be concluded that the design change is a critical variable to the effectiveness of C&D waste management.

Investment in C&D waste management

Investment in C&D waste management can help promote C&D waste management practices in a number of ways, typically including employing waste management workers, purchasing equipments and/or machines for waste management, developing and implementing waste management plans, motivating practitioners to manage C&D waste and improving workers' skills of waste management through vocational training.

For example, according to Chen et al. (2002), rewarding and penalizing mechanism with respect to on-site material handling can be used to effectively stimulate practitioners' efforts at minimizing C&D waste. This is backed by findings from Osmani et al. (2008), who stated that financial reward was perceived as a key incentive that could drive waste reduction during the project design. Furthermore, significant amount of C&D waste caused by various construction activities, such as cut-corner of construction formwork, poor plastering work, deformation during transportation and delivering, could be largely reduced if skills of waste management workers can be improved through vocational training (Wang et al., 2004b).

However, many industry practitioners were reluctant to join the activity of minimizing C&D waste simply because it meant higher costs (Mills et al., 1999). This indicates evidently that investment is a significant variable affecting the effectiveness of C&D waste management.

C&D waste management regulations

The importance of exhaustive governmental regulations for supporting C&D waste management has been extensively investigated. For example, Karavezyris (2007) confirmed that the government plays a crucial role in promoting C&D waste management practices by enforcing policies for the whole industry. The governmental regulation is identified as the most important factor for conducting C&D waste management in Shenzhen city of China by Lu and Yuan (2010).

Nevertheless, previous studies indicate that the effectiveness of implementing governmental regulations on C&D waste management in many economies is of limitation. For instance, although the Hong Kong government has implemented various types of regulations to minimize C&D waste, it was found by Tam (2008a) that the mandatory system for operating the waste management plan in construction projects significantly reduces the productivity of companies. This is echoed by findings from Shen and Tam (2002), arguing that legal measures are not effective for implementing environmental management in Hong Kong's construction sector. In all regulations in Bulgaria, C&D waste is mentioned jointly with municipal waste and the majority of measures envisaged are aimed at ameliorating municipal waste management (Hadjieva-Zaharieva et al., 2003). Furthermore, it was also reported by Kartam et al. (2004) that clear regulations from Kuwait Municipality are lacking for allowing and persuading contractors on using recycled products made from C&D waste.

In regard to governmental regulations in China, current policies for guiding the situation of C&D waste management in this economy are generally ineffective, although the promulgation of various C&D waste management laws and regulations since 1990s has improved the situation. The biggest problem is that most current policies are not detailed enough for guiding and enforcing C&D waste management. That the rules are too general is probably due to the relatively recent development of a modern system of law in China. At current stage, C&D waste managers are not able to benchmark the waste management practice in line with specific norms and standards. The implication is that for the management of C&D waste to be truly regulated, local regions need to develop their own detailed regulations, norms and standards. Furthermore, the allocation of responsibility for C&D waste management is ambiguous under current policies, which results in extensive illegal dumping of C&D waste in China. Hence, governmental regulation is a critical variable affecting the effectiveness of C&D waste generation.

Site space for performing waste management

Site space in this study refers to the space used for on-site waste collection and sorting. Since C&D waste is often the mixture of inert and organic materials, and mixed and contaminated waste is not suitable for reuse or recycling but generally disposed of at landfills directly (Shen et al., 2004), on-site waste sorting is widely perceived as an effective measure to ensure a higher rate of waste reuse and recycling. According to Poon et al. (2001b), site space was found to be the most important factor in Hong Kong when considering the selection of on-site waste sorting methods. Without a space layout pre-planned for waste collection and sorting, the temporary placement of sorting facilities and implementation of waste collecting sorting activities might disarrange other construction activities (Wang et al., 2010).

Evidence from previous studies clearly exhibited the benefits of on-site waste sorting. For example, Poon et al. (2001b) found that on-site waste sorting could increase the rates of reuse and recycling, and reduce the cost for waste transportation and disposal. Hao et al.'s (2008b) study revealed that the lifespan of landfills designed for receiving non-inert construction waste could be prolonged if waste sorting is performed. Furthermore, Shen et al. (2004) stated that the pollution resulted from the huge amount of C&D waste to the surroundings would be greatly lessened through effective implementation of on-site waste sorting. Therefore, sufficient site space for performing on-site waste sorting is important to C&D waste minimization.

Adoption of low-waste construction technologies

Low-waste construction technologies could help reduce, reuse or recycle C&D waste. Such technologies include prefabrication, innovative formwork and falsework, and low-waste structures, etc. Previous studies have acknowledged the potentials of low-waste construction technologies, such as prefabrication and modular structure in buildings, for minimizing C&D waste (Jaillon et al., 2009; Jaillon and Poon, 2008; Esin and Cosgun, 2007; Tam et al., 2007b; Poon et al., 2004a). Baldwin et al. (2007; 2008) suggested that for high-rise residential buildings, the main opportunities for waste minimization are related to the adoption of pre-casting and pre-fabricated techniques. A study by Jaillon et al. (2009) revealed that waste reduction is one of the major benefits when using prefabrication compared with conventional construction. The average wastage reduction level is about 52%. Tam et al.'s (2007b) investigation also showed that the average level of the conventional construction method is much higher than that of prefabrication in the trades of concreting, rebar fixing, plastering and tiling; particularly, adoption of prefabrication in concreting could achieve a 90% waste reduction compared with cast-in-situ. These facts imply that a wider use of low-waste construction technologies could reduce C&D waste generation considerably.

Waste management culture within an organization

Waste management culture within a construction organization is largely related to the influence of human factors on C&D waste minimization, such as practitioners' awareness of waste management. Previous studies have pointed out that practitioners' awareness of resource saving and environment protection is of vital importance to C&D waste minimization (Osmani et al., 2008; Yuan, 2008). For example, a study was conducted by Lingard et al. (2000) for revealing the understanding of both managers and site workers about waste reduction. Site workers' attitudes toward waste management were investigated by Teo and Loosemore (2001) and Chen et al. (2002). And years later, Osmani et al. (2006) carried out a research for assessing architects' views on the origins of design waste, situation of waste minimization design practices in the UK, as well as barriers to waste reduction. Findings of these studies demonstrated that it is crucial to take the attitudes of major practitioners into consideration when seeking a workable solution for reducing waste, and the findings also revealed that practitioners' attitudes toward waste reduction can differ between various groups of practitioners.

Furthermore, previous studies confirm that C&D waste management is perceived as a low priority in construction projects (Teo and Loosemore, 2001). Consequences caused by practitioners' weak awareness have been extensively investigated. Innes (2004) and Poon et al. (2004a), for example, found that about one-third of waste could arise from project design related decisions because designers attach relatively little importance to the potential for waste reduction when choosing building materials. Lam (1997) found that very few contractors have spent efforts in considering the environment and developing the concept of recycling building materials. Since contractors ranked timing as their top priority, their effort was always focused on completing the project in the shortest time, rather than the environment (Poon et al., 2001b). Therefore, improving practitioners' awareness of C&D waste management can make a significant contribution to the effective implementation of C&D waste management (Teo and Loosemore, 2001), and thus ameliorate waste management culture within the organization.

3.4 Variables affecting the economic performance of C&D waste management

Since environmentally friendly practice has not been on the high agenda to date

(Shen et al., 2006), whether the parties involved in C&D waste management (such as clients, contractors, engineers, etc.) could get extra economic benefits from embracing C&D waste management practices is the central concern to them. Thus, lack of economic incentives to manage C&D waste has been regarded as one major factor hindering the effectiveness of C&D waste management (Yuan et al., 2010).

The literature reveals that some attempts have been already made in the past decades for examining the cost-effectiveness of C&D waste management. For example, based on pertinent economic factors (such as transportation, labor, and disposal costs), Mills et al. (1999) conceived a proper waste management plan to choose a most cost-effective waste management plan. A benefit-cost analysis was performed by Begum et al. (2006) to investigate the feasibility of waste minimization through the employment of several mathematical equations. A model was developed by Duran et al. (2006) to assess the economic viability of creating markets for recycled C&D waste under different economical instrument scenarios. Furthermore, the economic consideration in recycling concrete waste was examined through a comparative study on costs and benefits between the current practice and the concrete recycling method (Tam, 2008a).

Economic benefits of C&D waste management

Economic benefits that can be gained from C&D waste management are enormous, typically including the possibilities of selling specific waste materials and the removal from site of other wastes at no charge or reduced cost, with a subsequent reduction in materials going to landfill at a higher charge (Snook et al., 1995). These on one hand will benefit the construction companies in terms of cost reduction (Guthrie et al., 1999), and thus increase contractor's competitiveness through lower production costs and a better public image (Begum et al., 2006). On the other hand, they can encourage reuse and recycling of waste materials thereby slowing down the depletion of limited landfill capacities (Hao et al., 2008b). Furthermore, economic benefits of performing C&D waste management can also be explicitly comprehended in line with the C&D waste management hierarchy, i.e. waste reduction, reuse, recycling and disposal, which has been thoroughly reviewed in Chapter 2. Processes of C&D waste reduction, reuse and disposal can diminish the total amount of waste to be dumped in landfills, which not only reduces the transportation cost for transferring C&D waste from construction site to landfills, but also decreases the money that would be paid for waste disposal. In addition, additional income can be generated by recycling and selling waste materials. Therefore, primary variables influencing the economic benefits of C&D waste management include: (1) saving in waste transportation cost from construction site to landfills, (2) saving in cost for disposing of waste at landfills, and (3) revenue from selling waste materials.

Costs of C&D waste management

While obtaining the above economic benefits from the conduct of C&D waste management, construction project stakeholders have to bear multifarious associated costs as well. By carrying out a benefit-cost analysis on the economic feasibility of waste minimization, Begum et al. (2006) presented that total costs are all the incremental costs associated the management of C&D waste, which mainly include the collection and separation costs of waste materials, the total costs of reusing and recycling waste materials and the transportation cost. According to Wang et al. (2010), C&D waste on-site sorting should be an essential practice before the waste can be further processed since it is very helpful to enable a higher rate of reuse/recycling. Nevertheless, on-site waste sorting will increase the costs of waste management as it requires investment in workers and equipments for waste sorting. Furthermore, construction companies should pay for the charging fee when disposing of C&D waste into landfills. In summary, the diverse costs of C&D waste management include: (1) cost of C&D waste collection, on-site sorting and separation, (2) cost of waste reuse, (3) cost of waste recycling, (4) cost of waste transportation from construction site to landfills, and (5) cost of disposing of waste at landfills.

Based on the discussions above, major variables affecting the economic performance, i.e. benefits and costs, of C&D waste management are:

- Cost of waste collection, sorting and separation;

- Cost of waste reuse;
- Cost of recycling;
- Cost of waste transportation from construction site to landfills
- Cost of disposing of waste at landfills;
- Penalty paid due to illegal dumping of waste;
- Revenue from selling waste materials;
- Saving in waste transportation cost from construction site to landfills; and
- Saving in cost for disposing of waste at landfills.

3.5 Variables affecting the environmental performance of C&D waste management

It has been widely acknowledged that C&D waste handling and processing by nature is not environmentally friendly due to its enormous adverse impacts on the environment. Fundamentally, C&D waste management can harmfully affect the total environment in many ways, such as running up a large amount of land resources for waste landfilling (Poon et al., 2003), harming the surroundings by hazardous pollution, and wasting natural resources (Esin and Cosgun, 2007). A synthesis of previous studies, governmental legislations and reports determined that five variables are critical to the environmental performance of C&D waste management systems, which are:

- Land consumption due to waste landfilling;
- Water pollution;
- Noise emission;
- Air pollution; and
- Environmental impacts of illegal waste dumping on public living environment.

Land consumption due to waste landfilling

Significant amounts of C&D waste are annually generated globally. The study by Sandler and Swingle (2006) showed that the US construction industry contributes to a large amount of waste to the MSW stream, with approximately 136 million tons of building-related C&D debris being generated each year, out of which only 20-30% is recycled. In the UK, it was reported that every year around 70 million tons of C&D materials and soil ended up as waste (DETR, 2000), and the wastage rate in the UK construction industry was as high as 10-15% (McGrath and Anderson, 2000). In Australia, C&D waste accounts for 16-40% of the total solid waste generated (Bell, 1998). In Hong Kong, according to the report by the Environment Protection Department (EPD), about 2,900 tons of C&D waste was received at landfills per day in 2007 (HKEPD, 2007). In addition, China produces 29% of the world's MSW each year, of which construction activities contribute for nearly 40% (Wang et al., 2008).

Faced with the huge amount of C&D waste, however, landfill is still an important channel for handling C&D waste in many economies. This has been evidenced clearly by many publications. For instance, US EPA (2003) estimated that 52% of the building-related C&D materials were discarded in 2003, much of which went to specifically designed C&D landfills. In Wales of UK, the official trend data showed no improvement on C&D waste being diverted from landfills in the past four years. 38% of generated waste is used for landfill and only eight years of landfill space remains in this region (WRAP, 2010). Furthermore, it was reported that Australia has a strong dependence on landfills for C&D waste management, with 43% of C&D waste going into landfills in 2002 (ABS, 2007). Therefore, in order to deal with C&D waste, more and more habitat will be occupied when pristine land is used for new landfills or there are expansions of existing landfills.

Water pollution

The inappropriate management of C&D waste is causing a wide range of environmental problems, among which a typical one is water pollution. C&D waste can enter waterways through various channels such as storm-water drains, and may be a major reason for water pollution. Any leak of suspended solid materials and/or waste leachate to a watercourse may have very damaging environmental effects. Therefore, effective C&D waste management should avoid discharging water-borne pollution.

Water pollution can also be resulted from C&D waste from sources such as solvents or chemically treated wood. Additionally, a study by TuTech (2004) stated that in Sri Lanka, illegal dumping is widely happening and consequently, illegally dumped C&D waste causes underground water pollution, mosquito breeding, and drinking water contamination, threatening public health. It can also cause dangerous blockages of storm-water drains, preventing monsoon runoff and causing floods and promoting mosquito breeding.

In a report by Symonds (1999), C&D waste recycling is deemed to be a process having many negative impacts on water quality, including:

(1) The breaking up, crushing, sorting and stockpiling of C&D waste-derived aggregates is likely to generate pollution of surface and groundwater by fuels and lubricants used in plant and machinery; and

(2) More complex C&D waste processing and sorting systems are found at fixed C&D waste recycling centers, and they will generate additional impacts, of which the most serious is potential pollution to the water environment as a result of the washing of C&D waste-derived aggregates to remove unwanted fractions (such as wood and plastic).

Noise emission and air pollution

C&D waste management can change the nearby air quality considerably by releasing pollutants (including noise and air pollution) into the air. Firstly, C&D waste generation, collection and separation will influence the air quality of construction sites by causing noise emission and dust discharges. Secondly, transporting aggregates, whether by road or rail, generates further impacts in the form of noise, vibration, dust and air pollution, and contributes to the visual and severance impacts associated with existing infrastructure (Symonds, 1999). Thirdly, the breaking up, crushing, sorting and stockpiling of C&D waste-derived aggregates is also likely to generate some air and noise pollution (from the use of internal combustion engines) (Symonds, 1999). Also, demolition activities will increase dust and noise levels which both lead to poor air quality (Leigh and Patterson, 2005). In addition to causing soil pollution and water pollution, landfills emit significant greenhouse gases. Landfills produce significant quantities of methane as waste decomposes over time and this greenhouse gas is 21 times more harmful than carbon dioxide in terms of its global warming impact (TuTech, 2004).

<u>Environmental impacts of illegal waste dumping on public living environment</u>

Illegal C&D waste dumping is the unlawful deposit of C&D waste onto land. In this illegal action, waste materials have been dumped, tipped or otherwise deposited onto land where no license or approval exists to accept such waste. Illegal C&D dumping varies from small bags of rubbish in an urban environment, such as street-side, to larger scale dumping of waste materials in isolated areas, such as rivers and mountains.

Illegally dumped C&D waste can adversely affect the public living environment in many aspects. As was mentioned by Yuan (2008), the living surroundings were substantially affected, such as polluting municipal rivers with illegally dumped waste and hindering the city subway construction activities by disposing of C&D waste illegally. More importantly, illegally dumped C&D waste generates hazardous wastes. It is a threat to rivers, lakes, air, land, oceans and ultimately to the public health. The practice of discarding hazardous C&D waste, which is highly toxic in nature, into rivers is highly hazardous to the environment. It has a severe adverse impact on the quality of water. When disposed of improperly; it contaminates ground and surface water supplies. As a result, it contaminates drinking water which in turn affects public health as well as aquatic life.

Such unfair actions not only pollute the environment but also pose serious health hazards. Breast cancer, prostate cancer and childhood brain disorders are increasing at an alarming rate and the increasing rates of contamination and pollution have only furthered these health problems. There is also a rise in certain maladies like autism and learning disabilities. The places where waste is illegally dumped are often freely accessible to people, including children, who may be seriously injured when coming in contact with hazardous chemicals.

3.6 Variables affecting the social performance of C&D waste management

C&D waste management activities also engender a series of social impacts. There are social impacts from C&D waste management activities, such as waste generation, collection, sorting, reuse, recycling, transportation and disposal. The comprehensive review on existing literature, governmental legislations, guidelines and reports in this study has led to the identification of eight variables influencing the social performance of C&D waste management. They are:

- Practitioners' awareness to manage waste;
- Provision of job opportunities;
- Physical working condition;
- Impacts on long-term health;
- Safety of workers in conducting C&D waste management;
- Public satisfaction about C&D waste management;
- Impacts of illegal waste dumping on the social image; and
- Public appeal for regulating illegal waste dumping.

<u>Practitioners' awareness to manage waste</u>

This variable concerns how industry practitioners' awareness will change while carrying out C&D waste management activities. In a way, promotion of practitioners' awareness about C&D waste management is helpful for raising awareness of the general public to protect natural resources and minimize C&D

waste.

Practitioners' awareness to manage waste has been widely recognized as an important factor affecting C&D waste management performance. As concluded by Lu et al. (2010), raising practitioners' awareness can be very effective for reducing C&D waste generation rate. In construction projects, practitioners' awareness about waste management is reflected in their attitudes and behavior toward waste management. Existing research into practitioners' attitudes and behavior toward waste management has been extensively discussed in Chapter 2. Normally, practitioners' attitudes and behavior toward waste management will vary between individuals, thereby resulting in different effects on C&D waste management performance.

Provision of job opportunities

C&D waste management can contribute to society by creating new job opportunities. It was concluded that diverting C&D debris from landfills and reselling, remanufacturing, or recycling the material can create jobs and business opportunities, reduce environmental degradation, and provide low-income residents with job skills For example, in Minnesota, USA, manufacturing using recycled materials supported almost 9,000 jobs (Leigh and Patterson, 2005).

In construction projects, waste management activities provide a wide array of jobs requiring different levels of job knowledge and skills. The waste collection phase provides low skilled and entry-level workforce opportunities, while activities, such as separation of waste materials, disassembly of buildings, and remanufacture of recycled materials, not only require technical knowledge but also basic job skills.

Physical working condition

Generally, workers for performing C&D waste management (such as waste collection, sorting, separation, reuse, recycling and disposal) are required to work in an environment which includes exposure to poor or harmful physical working conditions with frequent exposure to minor injuries or health hazards.

Considering the high frequency of exposure to hazardous materials, the physical working condition is of paramount importance to the health of workers participating in C&D waste management. Since training of workers in the areas of waste minimization and deconstruction techniques has a positive effect on a project, it is regulated by many authorities that waste-handling workers should receive training such as the skill of using large equipment and skill of handling hazardous materials (Chini and Bruening, 2005). The overall aim of these regulations is to prevent or reduce the harm caused by waste minimizing activities.

However, it is frustrating to see that in many economies, workers without any training have been employed for performing C&D waste activities. For example, in Turkey, although the Ministry of Works has adopted strict measures for workers health and working condition, such as the ‘Regulations for Health and Safety of Construction Workers’, it was found that in practice contractors are known to employ only unskilled labor for most manual work (Elias-Ozkan, 2005). These workers would experience very dangerous working conditions, handling hazardous waste without physical or social protection. Hence, the physical working condition is identified as a significant variable that can affect the social effectiveness of C&D waste management.

Impacts on long-term health

A number of pollutants can arise from C&D waste and they might impact the long-term health in different ways. According to the New Zealand OSH (Occupational Health and Safety), the main hazards to long-term health during demolition work are asbestos dust, lead poisoning, toxic fumes from gas cutting of galvanized steel, toxic substances present on site, synthetic mineral fibers, polychlorinated biphenyls (PCBs), and silica dust (Storey et al., 2005). Hazardous or toxic materials will increase the potential of contaminating materials that are being sorted for recycling and will also raise the potential of human health risks during disassembly (Chini and Balachandran, 2002). Therefore, the long-term environmental impact of C&D waste production and disposition needs more attention from city and county authorities so that the adverse impacts of C&D waste management activities can be reduced (Suarez and Malave, 2002).

Safety of workers in conducting C&D waste management

Site safety refers to the protection of workers from potential operational hazards. Safety hazards can occur in C&D waste management activities. For example, the deconstruction of a building involves the stripping of both structural and non-structural components. In the case of structural components, the workers should be aware of critical building supports and ensure that structural collapse is prevented at all times (NAHB Research Center, 2001). Furthermore, in demolition works, workers also need protection from falling while working in elevated parts of the building, protection from falling objects, fire protection, and protection from the collapse of the whole building (Macozoma, 2001).

Safety is a big issue in C&D waste management and thus many regulations have been planned to mitigate the safety hazards to workers. In the Netherlands, special courses are provided for the training of the workers on construction sites. An organization called VOS (training for demolition) has provided several courses at different levels. It is required that C&D waste workers on site should have at least completed one of those courses (Dorsthorst and Kowalcsyk, 2005). In addition, the UK Health and Safety Executive (HSE) has issued a series of health and safety guidance for construction including waste handling and processing activities. These are used to help all those involved in C&D waste management process, from client and designer to contractors and individual workers, to identify the main causes of accidents and ill health and to explain how to eliminate the hazards (Hurley and Hobbs, 2005).

Public satisfaction about C&D waste management

Public satisfaction about C&D waste management refers to the satisfaction level of the general public with C&D waste related activities. This variable is used to measure the overall impact of C&D waste related activities on the life quality of the people that can be influenced. It is a qualitative variable and its value should be determined by consulting nearby residents.

Generally, C&D waste activities can influence the life of nearly residents in many ways. For example, C&D waste activities can cause noise, odor, dust emissions, chemical particulate emissions, toxic gas and water pollution. Health problems relating to noise and air pollution due to waste management activities have become increasingly serious (CIRC, 2001). C&D waste might scatter on the road while being transported and thus affect the city environment. Furthermore, in some countries, streets and rivers in suburbs have been blocked by C&D waste that is inappropriately dumped (Yuan, 2008).

Impacts of illegal waste dumping on social image

Besides resulting in economic and environmental impacts, illegal waste dumping can also have impacts on the social image. As mentioned above, C&D waste dumped illegally will influence the city image by obstructing the road and river. Furthermore, extensive illegal C&D waste dumping will lead to a vicious circle in which more and more waste is dumped illegally. As a consequence, this makes it more difficult to regulate C&D waste dumping behavior.

Public appeal for regulating illegal waste dumping

In some regions, illegal waste dumping has been occurring extensively over the past two decades. Due to environmental concerns, also construction firms face pressure to act according to the principle of sustainability, such as waste reduction, reuse and recycling in order to foster resource preservation and emission avoidance, there is a strong public appeal to regulate C&D waste disposal activities (Schultmann and Sunke, 2007). Among which an important one is to govern the behavior of illegal waste dumping.

3.7 Formulation of major variables for assessing the effectiveness of C&D waste management

Based on the discussions in previous sections, a list of major variables affecting the effectiveness of C&D waste management systems were formulated, which is shown in Table 3.2. These variables form the base for establishing a dynamic model for evaluating the effectiveness of C&D waste management.

Table 3.2: Major variables affecting the effectiveness of waste management

Dimensions	Code	Variables
C&D waste generation	WG1	Design changes
	WG2	Investment in C&D waste management
	WG3	C&D waste management regulations
	WG4	Site space for performing waste management
	WG5	Adoption of low-waste construction technologies
	WG6	Impact of waste reduction cost
	WG7	Waste management culture within an organization
Economic performance	Ec1	Cost of waste collection, sorting and separation
	Ec2	Cost of waste reuse
	Ec3	Cost of waste recycling
	Ec4	Cost of waste transportation from construction site to landfills
	Ec5	Cost of disposing of waste at landfills
	Ec6	Penalty paid due to illegal dumping of waste
	Ec7	Revenue from selling waste materials
	Ec8	Saving in waste transportation cost from construction site to landfills
	Ec9	Saving in cost for disposing of waste at landfills
Environmental dimension	En1	Land consumption due to waste landfilling
	En2	Water pollution
	En3	Noise emission
	En4	Air pollution
	En5	Environmental impacts of illegal waste dumping on public living environment

Social dimension	So1	Practitioners' awareness to manage waste
	So2	Provision of job opportunities
	So3	Physical working condition
	So4	Impacts on long-term health
	So5	Safety of workers in conducting waste management
	So6	Public satisfaction about C&D waste management
	So7	Public appeal for regulating illegal waste dumping
	So8	Impacts of illegal waste dumping on social image

3.8 Summary

The overall objective of this chapter was to identify major variables affecting the effectiveness of C&D waste management systems. This was mainly achieved by two research activities. One was understanding and defining the term 'effectiveness of C&D waste management'. The other was, in line with the definition, identifying major variables affecting the effectiveness of C&D waste through an extensive literature search and analysis. As a result, 29 variables concerning four aspects, namely, C&D waste generation, economic performance, environmental performance, and social performance of C&D waste management, were identified.

The next Chapter presents an overview of the SD approach that was adopted to establish a dynamic model for this study.

CHAPTER 4 Introduction to the Methodology of System Dynamics

4.1 Introduction

As mentioned in Chapter 1, the overall aim of this study was to construct a dynamic model for evaluating the effectiveness of C&D waste management. It was anticipated that in the model, the economic performance, environmental performance and social performance associated with C&D waste management would be collectively examined. More importantly, the dynamic interactions between all the variables involved in the evaluation system would be revealed. Furthermore, to facilitate a comprehensive understanding of why SD approach is tailor-made for achieving the objectives of this study, an overview of SD is provided. The chapter ends by presenting a typical five-phase modeling procedure adopted by previous studies in different disciplines that have used SD. The information provided in this chapter forms the basis for comprehending the contents of model development and simulation provided in succeeding chapters.

4.2 An overview of system dynamics

SD was originated by Jay Forrester (1961) in the late 1950s at the Massachusetts Institute of Technology (MIT) as a modeling methodology for analyzing decision-making problems within the discipline of industrial management. The unique characteristic of this approach is its capability to represent the real world. It can deal with the complexity, non-linearity, and feedback loop structures that are inherent in physical and non-physical systems (Forrester, 1994).

Although there are many definitions of SD, they all have the common theme that SD is concerned with developing models or representations of real-world systems of all kinds and examining their dynamics. It is mainly concerned with improving the behavior of problematic systems. The original definition of SD is that "it is the study of information feedback characterization of industrial enterprise to show how structure, amplification, and time delays interact to influence the success of the enterprise" (Forrester, 1961). Years later, Wolstenholme (1990) defined it as "a rigorous method for qualitative description, exploration and analysis of complex systems in terms of their processes, information, organizational boundaries and strategies that facilitate quantitative simulation modeling and analysis for the design of system structure and control." The *qualitative* and *quantitative* characteristics of this definition are further expanded in Table 4.1 below, which provides a summary of the steps involved in the method and their purposes.

Table 4.1: System Dynamics – a subject summary

Qualitative SD	**Quantitative SD**	
(Diagram construction and analysis phase)	(Simulation phase)	
	Stage 1	*Stage 2*
To create and examine feedback loop structure of system using resource flows,	To examine the qualitative behavior of all system variables	To design alternative system structures and control strategies based

represented by level and rate variables and information flows, represented by auxiliary variables. To provide a qualitative assessment of the relationship between system processes (including delays), information, organizational boundaries and strategy. To establish system behavior and to postulate strategy design changes to improve behavior.	over time. To examine the validity and sensitivity of system behavior to changes in (1) information structure (2) strategies (3) delays/uncertainties	on (1) intuitive ideas. (2) control theory analogies. (3) control theory algorithms. In terms of non-optimizing robust policy design. To optimize the behavior of specific system variables.

(Adopted from Wolstenholme, 1990)

Some years later, Wolstenholme (1997) broadened the definition by stating the *what*, *why*, *how* and *within* of the methodology as follows:

What: A rigorous way to help thinking, visualizing, sharing, and communication of the future evolution of complex organization and issues over time;

Why: For the purpose of solving problems and creating more robust designs, which minimize the likelihood of unpleasant surprises and unintended consequences;

How: By creating operational maps and simulation models which externalize mental models and capture the interrelationships of physical and behavioral processes, organizational boundaries, policies, information feedback and time delays; and by using these architectures to test the holistic outcomes of alternative plans and ideas;

Within: A framework, which respects and fosters the needs and values of awareness, openness, responsibility and equality of individuals and teams.

Wolstenholme (1990) also stated that the purpose of employing a SD approach is to deepen understanding of the relationship between the behavior of a system over time and its underlying structure and decision rules. Modeling and simulating through SD enables exploring *what-if* scenarios and policy tests in something approaching a laboratory setting, leading to growing confidence in particular policies (Richardson and Otto, 2008).

Recently, the SD Group at MIT's Sloan School of Management claimed that "What makes using SD different from other approaches to studying a complex system is the use of feedback loops. Stocks and flows help describe how a system is connected by feedback loops which create the non-linearity found so frequently in modern day problems. Computer software is used to simulate a SD model of the situation being studied. Running 'what-if' simulations to test certain policies on such a model can greatly aid in understanding how the system changes over time" (SD Group, 2009). Rodregues and Bowers (1996) proposed that the motivation to apply SD to project management could be attributed to various factors, typically including:

- a concern to consider the project as an integrated system rather than a sum of individual elements (the holistic approach);
- the need to examine major non-linear aspects typically described by balanced or reinforced feedback loops;
- a need for a flexible project model which offers a laboratory to experiment management's options, and
- the failure of traditional analytic tools to solve all project management problems and the desire to experiment with something new.

By referring to previous studies in terms of the application of SD, its typical strengths can be summarized in Table 4.2, which have been categorized under three headings by Winz et al. (2009), namely, flexibility, ease of uptake and adaptability, and ongoing testing and learning.

Table 4.2: Overview of the strengths of SD

Category	Explanation
Flexibility – can be used for a wide range of applications and supports working with multiple bottom line dimensions	➢ Multi-disciplinary projects: supports the use of qualitative and quantitative variables in models: relationships between variables can be defined on an ordinary scale, e.g. low, medium, high, as often used in the modeling of social system components. ➢ Cross-scalar: a nested set of models can be developed to address the problem at different scales.

	Modular object-oriented models: models often consist of different sub-models (or modules) increasing interchange-ability and re-usability. ➢ Supports a variety of project goals: the focus of any project can be on the model development process itself to support consensus building and team learning, the final model and its use in simulating system behavior under different scenarios, or both.
Established methodology, ease of uptake, transparency and adaptability	➢ The dynamic nature of the model allows users to quickly become familiar with modeling and simulation as they are encouraged to alter the model structure, parameters and data on their own, and explore model capabilities and outcomes. Transparency is achieved through interaction – during the model development process as well as the experimentation with model output. It is a crucial factor in client understanding and thus in the building of trust, acceptance, and sense of ownership in the model and its results. ➢ Computer software (e.g., *iThink*®, *Vensim*®, *Stella*™) is widely available though not in-expensive and intuitive interfaces significantly reduce the need for programming. Compilation and simulation are fast. There is a wide variety of model outputs including tables, graphs and diagrams, wide range of sensitivity analysis capabilities, and in-built error checking capabilities. ➢ Parameters do not necessarily need to be fixed before simulation. They can be either manually or

	dynamically adjusted.
Foresighting, ongoing testing and learning, stakeholder participation	➢ Simulation allows for the continuous testing of assumptions and sensitivity analysis of parameters, with few restrictions on problem presentation so long as variables can be identified and relationships defined. Assumptions can be implicit or explicit and are used to make problems mathematically tractable. No simplification is required to make the model mathematically tractable and no objective function needs to be specified. ➢ Methods are available to support consensus building and team learning throughout the different stages of the model development process.

4.3 Basic elements of system dynamics modeling

Basic elements of SD modeling include stock, flow, converter, and connector. These elements have been incorporated in developing various SD applications for solving different problems, although they might be displayed with different denotations in different computer software. In this section, the iThink® software package, which is adopted for SD modeling in this study, will be introduced, followed by addressing these basic elements to show how they can be incorporated together to constitute a SD model.

4.3.1 iThink software package

The model for evaluating the effectiveness of C&D waste management proposed in this study is visualized through iThink software package, which is especially designed for SD modeling by High Performance Systems Inc. (2006). As a popular tool for SD simulation (Shen et al., 2005; Hao et al., 2008b), the software iThink is considered suitable for model development and simulation in this study. It is a powerful tool for mapping and communicating interdependencies between processes and problems. It also allows the structure of a process or strategy to be rigorously linked to the associated dynamics. Its key features of mapping and modeling include:

- Intuitive icon-based interface simplifies model building;
- Stock-flow diagrams support the common language of Systems Thinking and provide insight into modeled business processes;
- Causal loop diagrams present overall causal relationships;
- Model equations are automatically generated and made accessible beneath the model layer; and
- Sub-models support hierarchical model structures;

The main iThink window is divided into four tabbed pages: *Interface*, *Map*, *Model* and *Equation*. Each tap represents a distinct layer in the model and each provides a different way of designing and presenting a model. The Map layer is for laying out the thinking in the form of a map; the Model layer is for transforming maps into models that can be simulated on a computer; the Interface layer makes it possible to transform a model into a compelling environment for learning; and the Equation layer lists all the equations that make up the model. Figure 4.1 to Figure 4.4 are screenshots illustrating an example of the four layers in software iThink.

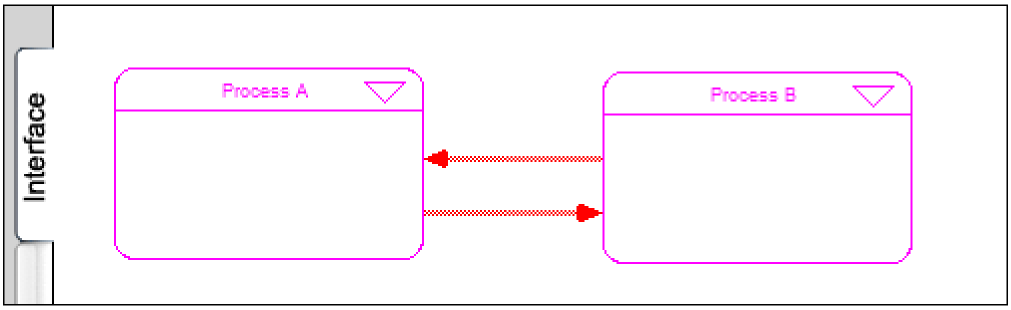

Figure 4.1: An example of the Interface layer

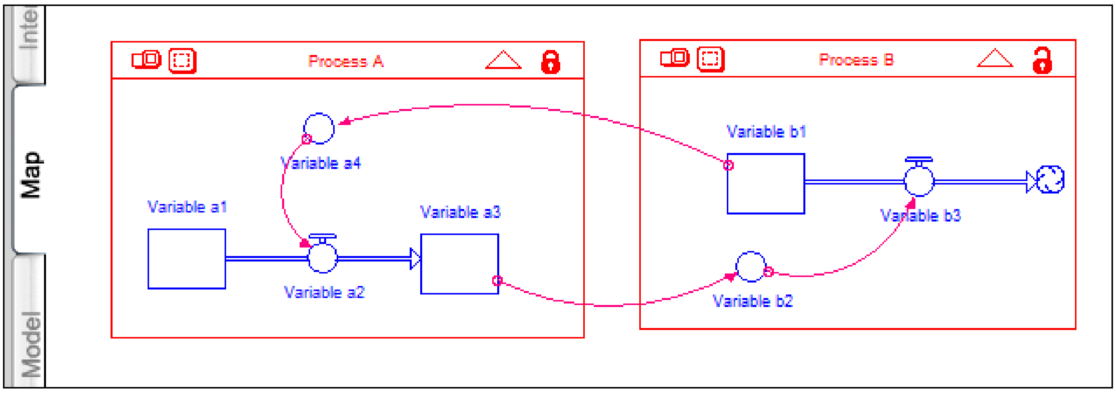

Figure 4.2: An example of the Map layer

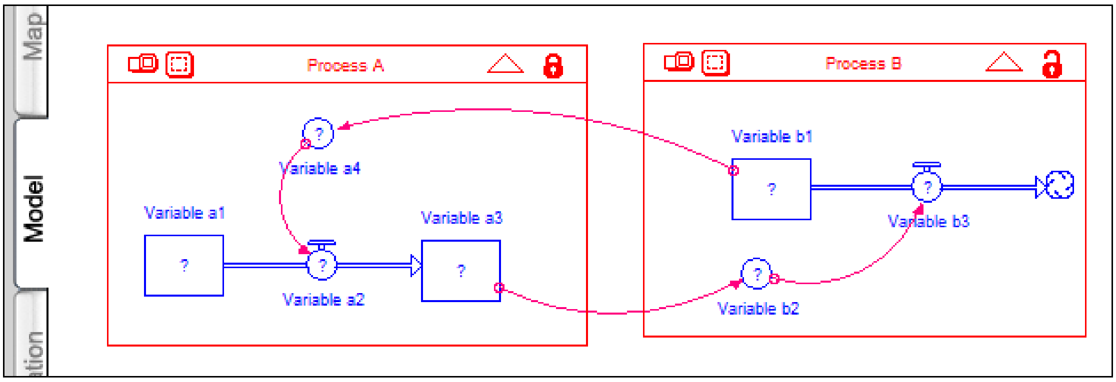

Figure 4.3: An example of the Model layer

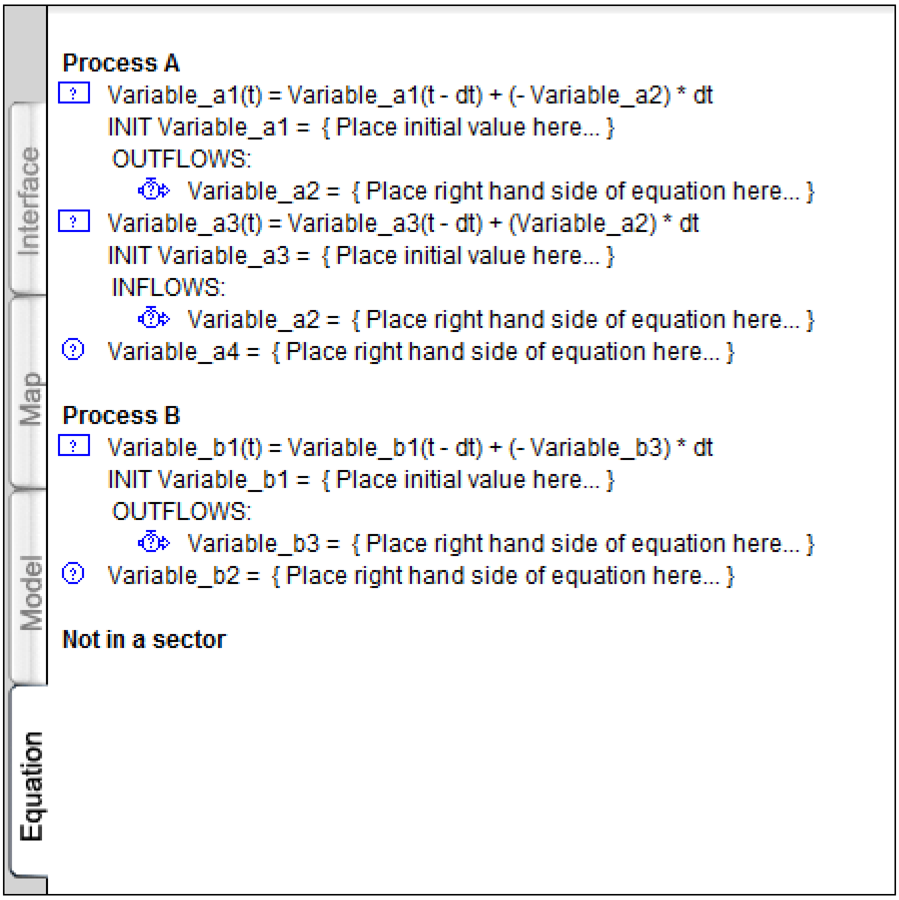

Figure 4.4: An example of the Equation layer

4.3.2 The basic elements for SD modeling

The iThink language is icon-based, and the icons are operational in nature. There are four structural elements (*stock*, *flow*, *converter*, and *connector*) in SD modeling, and each of them is represented by a particular icon in the software, as displayed in Figure 4.5. A detailed explanation of these elements is provided in the following paragraphs.

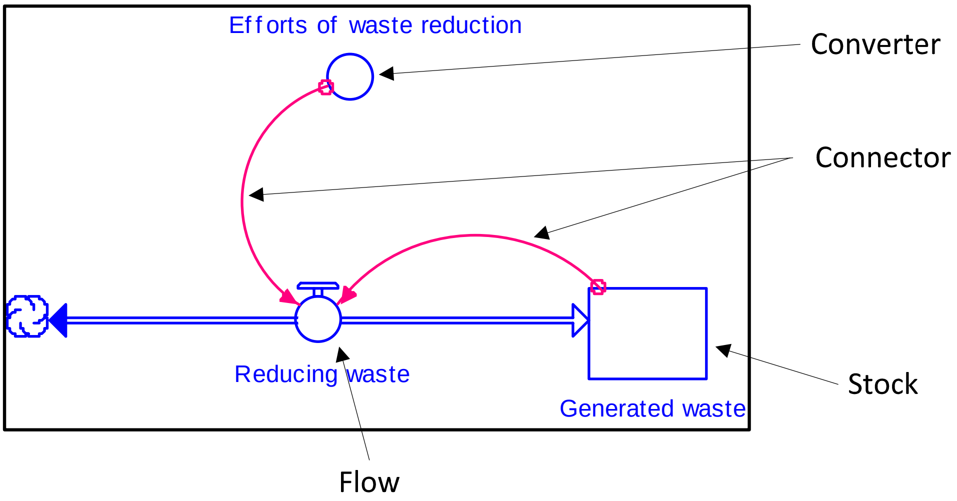

Figure 4.5: iThink's four basic components in a waste reduction model

<u>Stock</u>

Stocks, which are represented by rectangles, are the nouns of the iThink language and are basically accumulations. They collect whatever flows into them, net of whatever flows out of them. Stocks, in general, can be referred to as system state variables, as they describe the condition of the system and they would continue even if all the flows in the system were brought to a halt (Maani and Cavana, 2000). There are four types of stocks: *reservoirs*, *conveyers*, *queues*, and *ovens*. By far, the most frequently used type of stock is the reservoir. A distant second in frequency of use is the conveyor. The lineup of stocks appears in Figure 4.6.

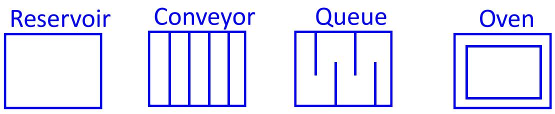

Figure 4.6: The four types of stocks

In Figure 4.5, for example, *Generated waste* is a *reservoir* stock for describing the total amount of waste produced over the survey period. This amount will fluctuate according to the influence that the converter (herein refers to ‘Efforts of waste reduction’) exerts on the flow (herein refers to ‘Reducing waste’).

A conveyor can be thought of as a moving sidewalk or a conveyor belt, transporting materials for a period of time until they get off. The transit time for a conveyor can be either constant or variable. Multi-inflows to a conveyor are allowed. Both capacity and inflow limit can constrain entry to a conveyor.

A queue can be viewed as a line of items awaiting entry into some process or activity (e.g. grocery store checkout line, airport ticket counter line, C&D waste handling queue). Queues are based on a FIFO (first in first out) operational rule. In other words, stuff enters the queue, and remains in line, waiting its turn to exit the queue.

On the other hand, an oven can be thought of as a processor of discrete batches of stuff. The oven opens its door; fills (either to capacity or until it is time to close the door); bakes its contents for a time; then unloads them in an instant.

The inflow to an oven can come from a reservoir or a queue.

Flow

Flows are the verbs of iThink. A flow serves as a vehicle to deliver information to or drain information from the stock. The value of a flow can be either positive or negative. A positive flow is an in-flow and will fill in the stock, and a negative flow is an out-flow draining the stock. While stocks depict how things *are* in a system, flows indicate how things *are going*. In this sense, stocks and flows are two inseparable components. Without flows, no change could actually occur in the system.

Figure 4.7 exhibits two types of flows provided by the iThink: uniflows and biflows. Uniflow stands for *unidirectional*, meaning that the flow will flow in one direction only. The direction of flow is indicated by the arrowhead. If the arrowhead points *into* a stock, the flow can only *fill* the stock. With uniflows, the flow volume will take on non-negative values only. On the other hand, biflows allow flow volume to go in *both* directions, either into or out of a stock. Therefore, they can take on any value. If a flow is specified as a biflow, another shaded arrowhead will also appear on the flow to point the direction of negative flow, as shown in Figure 4.7. It is worth noting that a biflow exists only in the situation of reservoir, and not exists in a conveyor, queue, or oven. And a uniflow can exist in any situation.

Figure 4.7: Two types of flows in iThink

Referring back to Figure 4.5, the indicated flow determines the amount and direction of change of the variable *Generated waste* and is updated at regular intervals during the simulation run. The relationships between the stock 'Generated waste' and the flow 'Reducing waste' are represented mathematically in SD by the equation:

$$Generated\ waste\ (t) = Generated\ waste\ (t-dt) + (Reducing\ waste)*dt$$

This equation shows clearly how the amount of waste generation changes over time depending on the rate of change in waste reduction and the current volume of generated waste.

<u>Converter</u>

The converter serves a utilitarian role in SD modeling. It holds values for constants, defines external inputs to the model, calculates algebraic relationships, and serves as the repository for graphical functions. They are called *converters* because that in general, they convert inputs into outputs. The advantage of converters is that they break complex flow equations into simpler components and make the model easier to understand. In terms of understanding the way in which the system works and can be modeled, converters are very important and are significant components of the system structure (Maani and Cavana, 2000).

<u>Connector</u>

As its name suggests, the job of the connector is to connect model elements. A connector is actually an information transmitter which allows information to pass between stocks and converters, stocks and flows, converters and converters, flows and flows. It is worth highlighting that connectors serve as information inputs and outputs, not inflows and outflows; that is, they only transmit information, without any stuff flowing through them.

4.4 Causal loops

Generally, the structure of a SD model is portrayed by causal loop diagrams which capture the major feedback mechanisms of a real-world system. A causal loop is a conceptual tool which reveals a dynamic process in which the chain effects of a cause are traced, through a set of related variables, back to the original cause (effect) (Maani and Cavana, 2000).

The causal loop diagram includes variables and arrows (which are called causal links) linking these variables together and assign (either + or −) on each link (see Figure 4.8). These signs have the following meanings (Kirkwood, 1998):

1. A causal link from one variable A to another variable B is positive (that is,

+) if either (a) A adds to B or (b) a change in A produces a change in B in the *same* direction (meaning increase or decrease at the same time).

2. A causal link from one variable A to another element B is negative (that is, −) if either (a) A subtracts from B or (b) a change in A produces a change in B in the *opposite* direction.

In general, there are two types of causal loops. These are Reinforcing (R) or positive feedback, and Balancing (B) or negative feedback. These represent the generic feedback processes for all causal loops. Reinforcing loops can represent growing or declining actions. They generally amplify or add to change in the system. Unlike a reinforcing loop, a balancing loop seeks stability or return to control, or aims for a specific target.

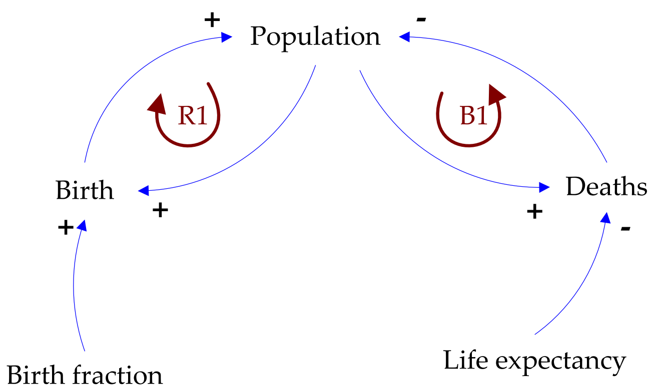

Figure 4.8: Sample of a causal loop diagram

(Adapted from Maani and Cavana, 2000)

Figure 4.8 shows a causal loop diagram of a simple population system, where population is increased by births and depleted by deaths. Births depend on the current population and the current average percentage of new births each year and deaths depend on the current level of the population and the average life expectancy. It shows clearly that the relationship between birth and population is a reinforcing process whereas deaths and population represent a negative feedback loop. It should be noted that there *positive* and *negative* should not be confused with *good* and *bad*. As Kauffman (1981) stated, whether feedback loop is considered positive or negative depends on what it does to changes in the system.

4.5 A five-phase modeling process for applying the SD approach

The general procedure in a SD modeling involves five major phases: problem recognition, system description, model formulation, model validation, and scenario analysis. Such a five-phase modeling process, as shown in Figure 4.9, has been suggested and adopted by many researchers (e.g. Sterman, 2000; Maani and Cavana, 2000; Coyle, 1996). This study also follows this procedure for model development and simulation.

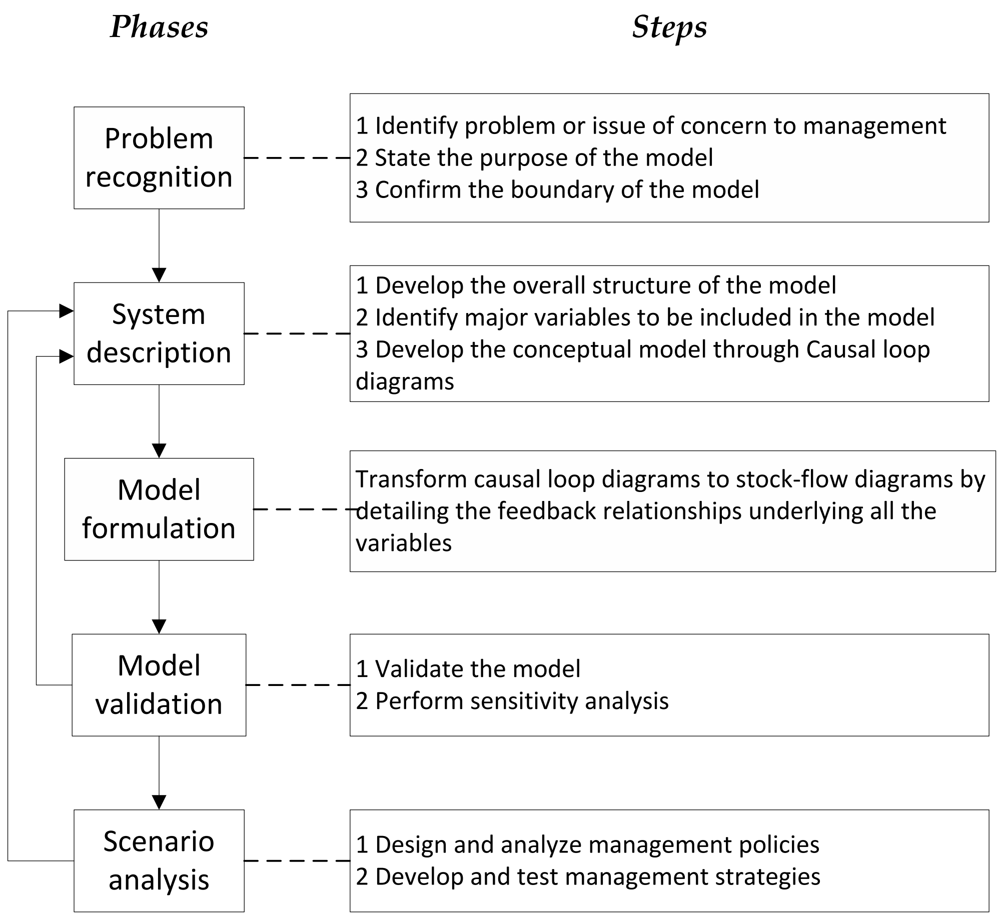

Figure 4.9: The five-phase procedure for the application of SD

<u>Stage 1: Problem recognition</u>

The first stage is to define the real-world problem to be understood and improved. In this stage, it is crucially important to figure out *what is the problem,* and *why it is a problem* (Sterman, 2000), as any study of SD application should have a clear purpose (Forrester, 1961). Statements of model purpose and the goals of a modeling effort serve two purposes: they focus a study initially and aid in judging the validity of the results (Richardson and Pugh, 1981). Another contributor to the importance of problem recognition is that the boundary of a model can be determined by dictating what should be included in and what should be excluded from the model during this stage (Richardson and Pugh, 1989).

Stage 2: System description

Once the problem has been clearly recognized, all essential variables should be identified and included in the model. The essential variables refer to those that can significantly influence the behavior of the system and be manipulated by decision makers to solve the problems. It is also worth noting that only the major variables should be included in the model to ensure the key behavior of the system is not obscured. Based on these identified variables, the system can be described by means of an influence diagram, mostly refers to as a *causal loop diagram* (Coyle, 1996).

Stage 3: Model formulation

If qualitative analysis through a causal loop diagram does not provide enough insight to solve the problem, the modeling process will have to proceed to Stage 3. In this stage, a stock-flow diagram will be formulated. Actually, the causal loop diagram and the stock-flow diagram are simply two different versions of the same model. The difference is that the former is written in arrows and words, and constructed in the hope of understanding the problem better; the latter is in equations and computer code, which allows us to simulate the model and conduct quantitative analysis (Coyle, 1996).

Stage 4: Model validation

The formal process that leads people to place confidence in a model is frequently referred to as the validation of the model (Richardson and Pugh, 1989). In this regard, many tests have to be made after model development for building up confidence in the model (Sterman, 2000). First, the model is tested to make sure the variables are meaningful in the real world. The behavior of the model is also examined by sensitivity analysis (undesirable and substantial changes in behavior patterns caused by small variable changes). Next, the model is tested to determine if it fits reality. The structure of the model is examined in terms of its recognizability to those most knowledge about the system and the reasonable fit between the variables and real data. In addition, the behavior of the model is examined to make sure that the model can explain the behavior patterns and behaves reasonably under extreme conditions.

Stage 5: Scenario analysis

Once the modelers have validated the structure and behavior of the model, the model then can be used to design and evaluate management policies for improvement.

4.6 Summary

This chapter provided an overview of the SD methodology and the software iThink which is used for model development and simulation in this study. The chapter also introduced a generic five-phase modeling process for creating and running a SD model.

The following chapter is to build a dynamic model for assessing the effectiveness of C&D waste management. The process in developing this model shows the application of the SD methodology which has been introduced above in this chapter.

CHAPTER 5 Development of a Dynamic Model for Assessing the Effectiveness of C&D Waste Management

5.1 Introduction

A model developed based on SD will enable the investigation of dynamic interrelationships among activities involved in managing C&D waste. The previous chapter provided a detailed introduction to the SD approach and how it could benefit the assessment of the effectiveness of C&D waste management. This chapter presents the development of a dynamic model for evaluating the effectiveness of C&D waste management by using SD. To provide the understanding of the model's development, this chapter starts with a schematic diagram depicting the procedures of developing the model. It continues with a brief description of the model, in which its purpose and boundaries are clearly defined. The three steps that gave birth to the model and ensured that it functioned logically are then explained. The first step provides an overview description of the model's structure, including the creation of four sectors to represent the separate parts of the model and connections in and across the sectors to represent their interrelationships. The second step constructs a conceptual model through the causal loop diagram, while the third and final step transforms the causal loop diagram into a stock-flow diagram using the four basic blocks (stock, flow, converter, and connector) of the iThink software thereby enabling the model to be effectively and efficiently simulated on a computer.

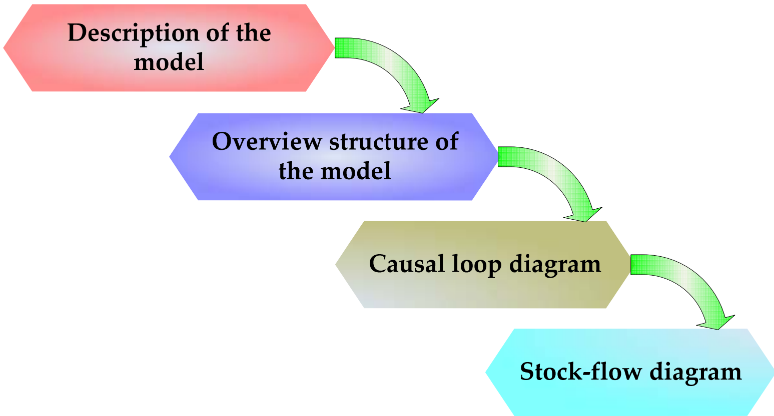

Figure 5.1: Schematic diagram of the procedure for developing the dynamic model

5.2 Description of the model

5.2.1 Purpose of the model

The model developed in this research is expected to fulfill three main purposes. The first purpose is to allow researchers and decision-makers involved in C&D waste management to understand the dynamics of the C&D waste management systems, particularly to comprehend the economic, environmental and social performance of C&D waste management from a dynamic point of view. The model functions as an experimental platform for examining the effects of implementing different management policies on the effectiveness of C&D waste management.

The second purpose of the model is to provide a solid basis for discussing major variables affecting the effectiveness of C&D waste management. The model's underlying theory explicitly defines the variables that are deemed to have major impacts on the effectiveness of C&D waste management. It is envisaged that subsequent discussions on the topic will encourage decision-makers to pursue effective C&D waste management more enthusiastically and vigorously.

The third purpose is to provide a utilitarian tool for illustrating the advantages and disadvantages of specific management policies that to be implemented. Once researchers and decision-makers have experimented with management policies for improving the effectiveness of C&D waste management, they will then be able to relay their findings to others through hands-on training using the model to simulate different policy scenarios. One example of this might be experimenting with the effect of establishing a waste management plan at the construction project level to see whether it will lead to an overall improvement in the effectiveness of C&D waste management.

5.2.2 Boundary of the model

In line with the principles of SD, it is important to define a boundary for the model from the outset of its development (Sterman, 2000). Only in this way, can the variables that should be included in or excluded from the model be determined. Since this study aimed at investigating the effectiveness of C&D waste management, the C&D waste management process, ranging from waste generation, reduction, reuse, recycling to waste disposal, is therefore the focus of the model.

Having a closer look at a typical C&D waste management process, five major nodes can be summarized, i.e., C&D waste generation, reduction, reuse, recycling, and disposal. These nodes exit somehow likes a chain and C&D waste flows from the beginning of the chain (waste generation) to the end (waste disposal). Currently a clear definition of the term *C&D Waste Chain* is absent. Inspired by the definition of *Value Chain* as stated in Porter (1998), the author of this thesis provides the following working definition of *C&D Waste Chain*:

> **C&D waste chain** refers to a chain that consists of a series of waste management activities. C&D Wastes pass through all activities of the chain in order and at each activity the volume of waste is minimized by various waste management activities.

It should be noted that the C&D waste chain is not a collection of independent waste management activities but a system of interdependent activities, which is a critical reason for the choice of SD as the approach for development of the model in this study.

Based on the above analysis, a conceptual model illustrating the boundary of the model and C&D waste chain can be developed, as shown in Figure 5.2. The four ellipses including *C&D waste chain*, *economic performance*, *environmental performance* and *social performance*, which are all located in the dotted rectangle area, form the boundary of the model. In other words, the model will be concentrated on examining interrelationships of variables affecting the economic, environmental and social performance of waste management activities throughout the C&D waste chain.

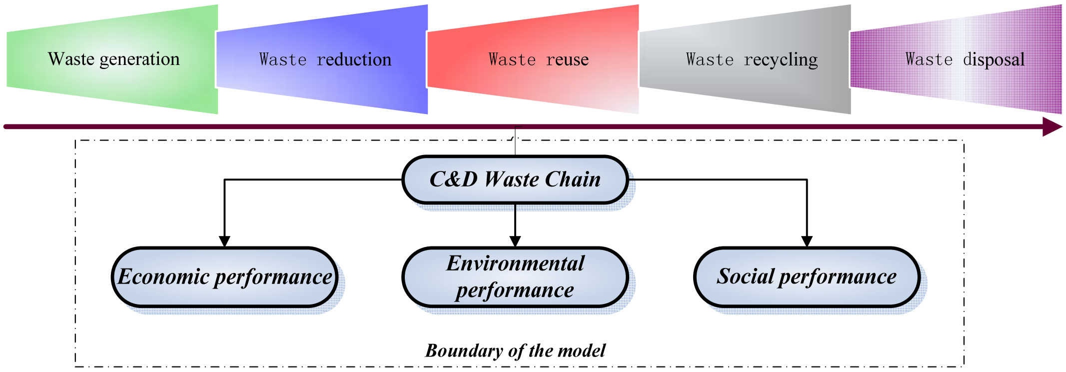

Figure 5.2: Boundary of the model

5.3 Overall structure of the model

In line with the model boundary defined in the above section, five subsystems comprise the model, namely, C&D waste generation, economic performance, environmental performance, social performance, and effectiveness of C&D waste management. A schematic diagram illustrating the interrelationships between these subsystems is shown in Figure 5.3. In the Figure, each arrow indicates the interrelationship that exists between the two subsystems concerned. The shared variables between any two interconnected subsystems will be interpreted later in the section of *stock-flow diagram*.

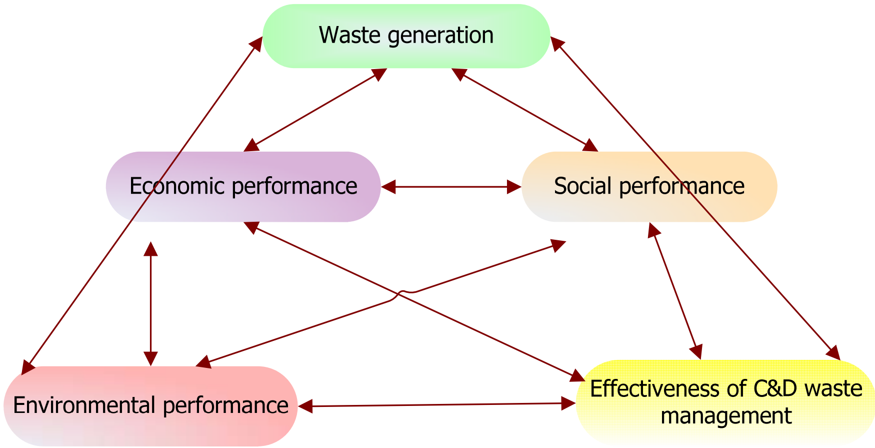

Figure 5.3: Overview of the model

5.4 Causal loop diagrams

The causal loop diagram is a conceptual tool which reveals a dynamic process in which the chain effects of a cause are traced, through a set of related variables, back to the original cause (effect). It aids in visualizing how interrelated variables affect one another. Normally, such a diagram consists of a set of nodes representing the variables connected together. The relationships between these variables, represented by arrows, can be labeled as either *positive* or *negative*. In the present study, each of the subsystems of C&D waste generation, economic performance, environmental performance, and social performance are formed by a series of causal loop diagrams. The following section expatiates on these causal loop diagrams.

5.4.1 Subsystem of C&D waste generation

It has been discussed in Chapter 3 that there are seven variables contributing to C&D waste generation, including design changes, investment in C&D waste management, C&D waste management regulations, site space for performing waste management, adoption of low-waste construction technologies, impacts of waste reduction cost, and waste management culture within an organization. By constructing these variables based on their interrelationships, the causal loop diagram of the subsystem of C&D waste generation which contains six feedback loops in total is formulated with the assistance of Microsoft Visio® (Figure 5.4). Among the feedback loops, one is positive (i.e. R1) and the other five are all negative (i.e. B1, B2, B3, B4 and B5). These feedback loops are further described in the following sections.

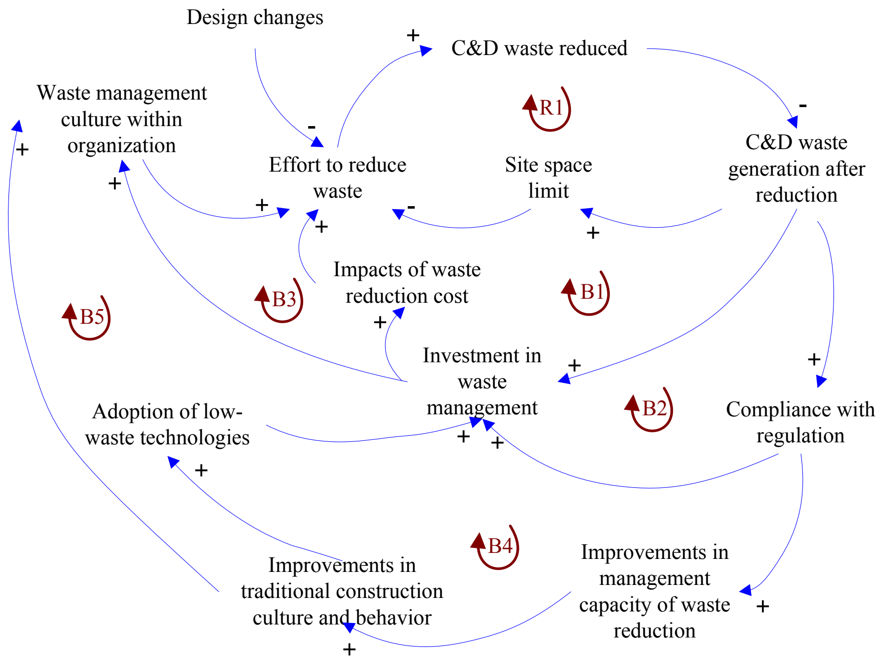

Figure 5.4: Causal loop diagram of the subsystem of waste generation

(In the causal loop diagram, a plus sign "+" indicates that the variables at the opposite ends of the arrow tend to increase in the same direction while a minus sign "-" indicates an inverse relationship.)

It should be noted from Figure 5.5 that the amount of reduced C&D waste can reinforce itself through the positive chain. Suppose that the reduction of C&D waste accelerates through implementing waste management strategies, a less amount of C&D waste will be produced on the construction site. As a consequence, limit of site space for conducting C&D waste management will be relieved (Poon et al., 2001b). That is, a less amount of C&D waste generation requires less site space for performing C&D waste management. If restraint of site space for implementing waste management declines, the effort committed to waste reduction will be increased (Wang et al., 2010). Finally, the speed of C&D

waste reduction will further accelerate due to increased efforts at waste reduction.

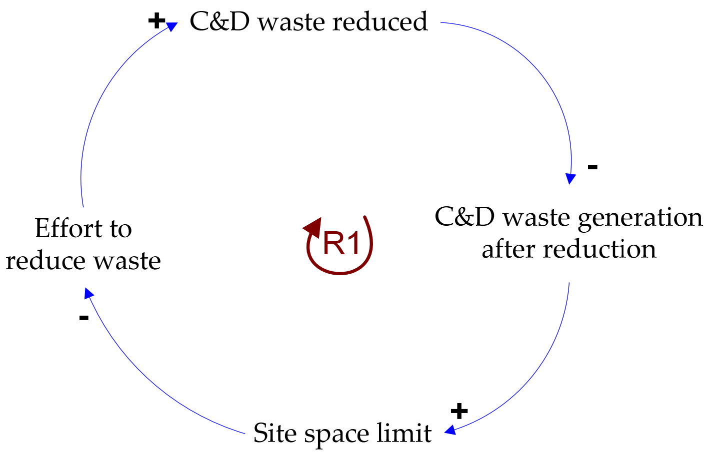

Figure 5.5: Positive feedback loop R1

In the negative feedback loop B1 (see Figure 5.6), a change of any variable, for example, C&D waste reduced, will eventually affect itself in a negative way. Suppose the reduction of C&D waste accelerates, then the volume of C&D waste generated on the construction site will decrease. As a result of decreased C&D waste generation, investment in waste management will decline (Yuan et al., 2010). In line with the decreased investment in waste management, the influence of waste reduction cost on C&D waste generation will decline, which corresponds to less efforts to reduce waste. Due to fewer efforts committed to waste reduction, the rate of C&D waste reduction will decrease eventually.

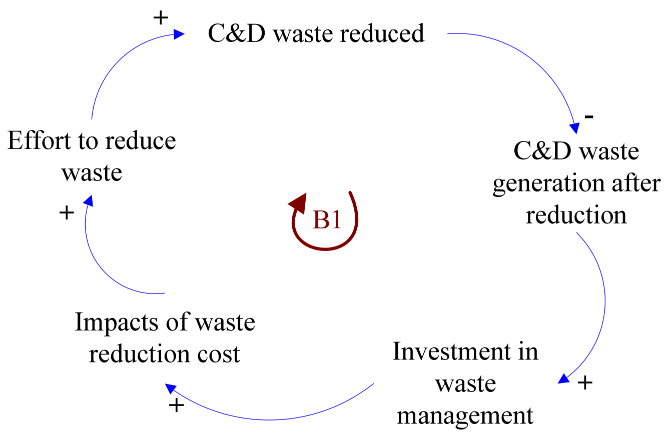

Figure 5.6: Negative feedback loop B1

The process of loop B2 is similar to the feedback loop B1. The only difference lies in the addition of variable *compliance with regulation*. When there is a larger amount of C&D waste generation, there will be a greater need for managers to be in compliance with C&D waste management regulations (Clark et al., 2006). Due to the higher efficiency of compliance with related regulations, more investment, as well as efforts to reduce waste, will be devoted to C&D waste management. Subsequently, these efforts may contribute to C&D waste minimization and eventually have a negative influence on the entire feedback loop.

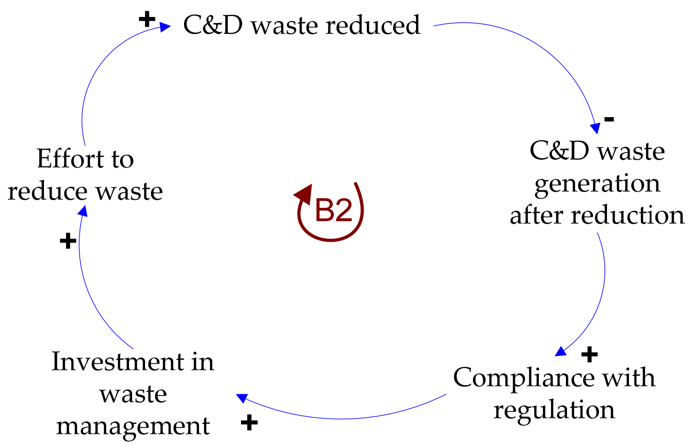

Figure 5.7: Negative feedback loop B2

Loop B3 (see Figure 5.8) is formed by adding the variable of *waste management culture within an organization* to the feedback loop B2. Similarly, a larger amount of C&D waste generation will lead to a greater need for managers to be in compliance with C&D waste management regulations, which then results in a larger investment in managing C&D waste (Clark et al., 2006). Better waste management culture within an organization can be fostered through the larger investment in waste management; on the other hand, better waste management culture within an organization will stimulate more efforts to reduce waste, which ultimately causes more C&D waste to be reduced (Chen et al., 2002).

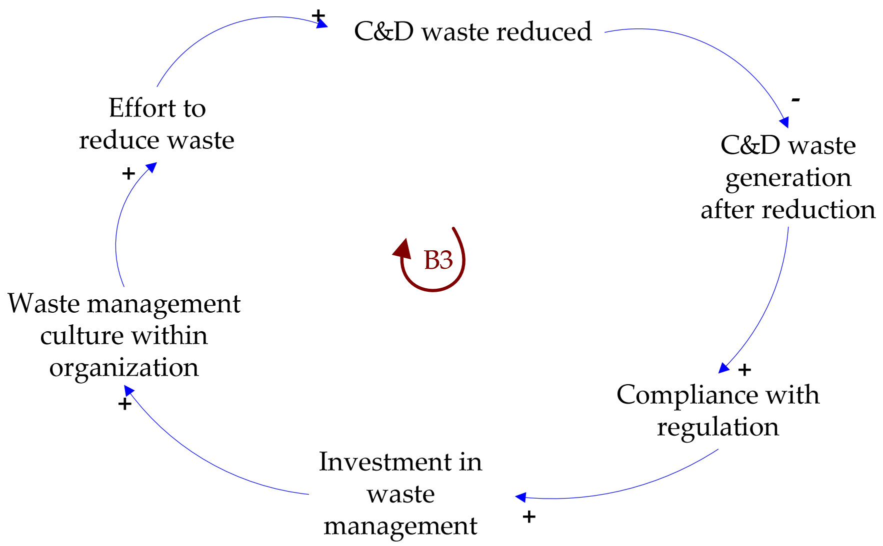

Figure 5.8: Negative feedback loop B3

In Figure 5.9, if there is a larger amount of C&D waste generation, it will request a larger demand to be in compliance with C&D waste management regulations (Lange, 1999), which then results in improvements in management capacity of waste reduction and traditional construction culture and behavior (Chen et al., 2002). Subsequently, the level of the adoption of low-waste construction technologies will increase, which requires a larger investment in waste management accordingly (Chiang et al., 2006). Similar to the mechanism in the feedback loop B3, the larger investment in waste management will promote the waste management culture within the organization and finally contribute to C&D waste reduction through a series of chain effects in the loop.

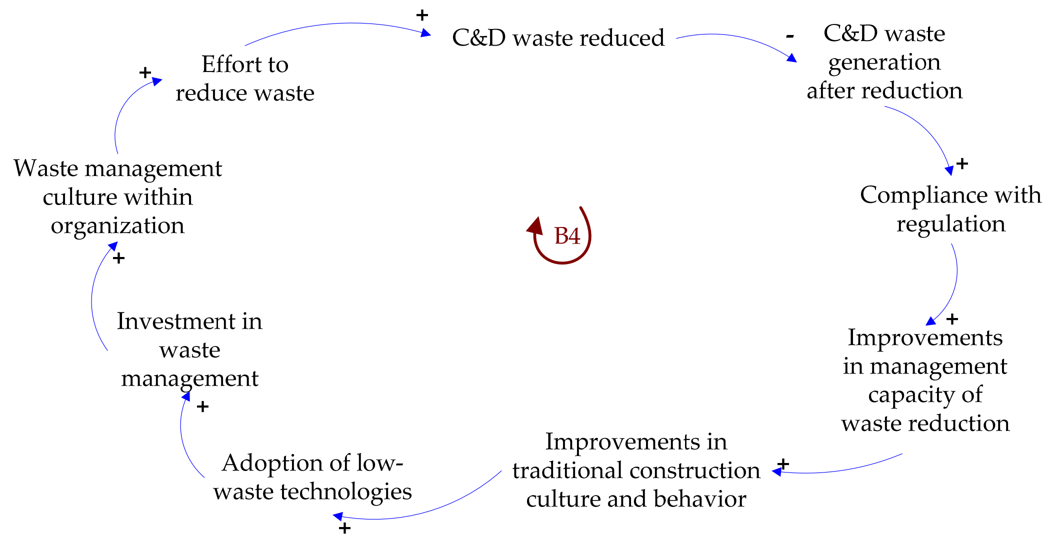

Figure 5.9: Negative feedback loop B4

The feedback loop B5 shown in Figure 5.10 indicates a similar influence loop as the feedback loop B4. The only difference is that in the loop B5, the improvements in management capacity of waste reduction lead to improvements in traditional construction culture and behavior directly (Wang and Yuan, 2009).

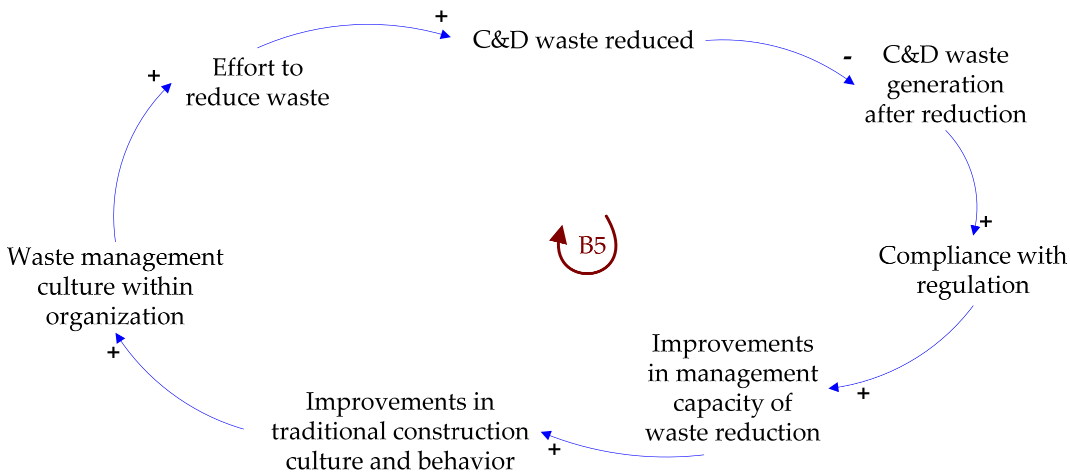

Figure 5.10: Negative feedback loop B5

5.4.2 Subsystem of economic performance

It has been discussed in Chapter 3 that there are nine variables affecting economic performance of C&D waste management, including cost of waste collection, sorting and separation, cost of waste reuse, cost of recycling, cost of waste transportation from construction site to landfills, cost of disposing of waste at landfills, penalty paid due to illegal dumping of waste, revenue from selling waste materials, saving in waste transportation cost from construction site to landfills, and saving in cost for disposing of waste at landfills. By connecting these variables based on their interrelationships, the causal loop diagram of the subsystem of economic performance which contains sixteen feedback loops in total is established (Figure 5.11). Among the feedback loops, three are positive (i.e. R1, R2 and R3) and the other thirteen are negative (i.e. B1 to B13). All interrelationships among these feedback loops are expounded as follows.

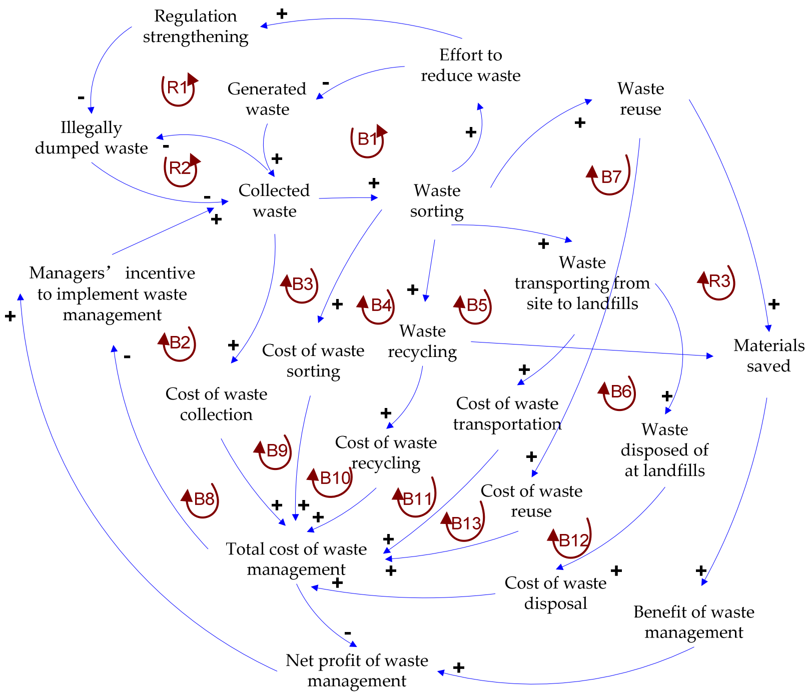

Figure 5.11: Causal loop diagram of economic performance subsystem

In the feedback loop R1 (see Figure 5.12) of the subsystem of economic performance, suppose that there is an increase in the amount of illegally dumped waste, this indicates a decrease in the volume of collected waste on the construction site, which results in less waste to be sorted for further processing. Subsequently, the smaller amount of sorted waste reflects fewer efforts of the local government for waste reduction. Since regulation is one of the effort clusters for promoting waste reduction, fewer efforts of the local government to reduce C&D waste will cause less actions of the government to strengthen waste reduction regulations. Consequently, loose waste reduction regulations allow more waste dumped in inappropriate places, instead of being disposed of at landfills. Therefore, this feedback loop is a reinforced loop.

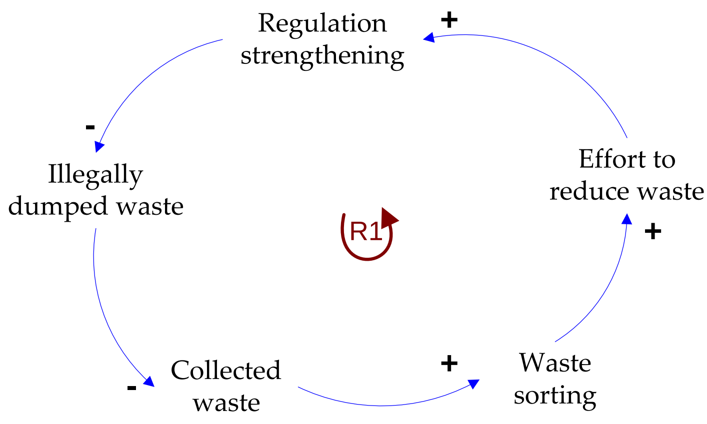

Figure 5.12: Positive feedback loop R1

Positive feedback R2 (see Figure 5.13) only contains two variables. In the feedback loop, a larger amount of C&D waste which is dumped illegally causes a smaller volume of waste to be collected on the construction site, and then the smaller volume of collected waste indicates more waste will be disposed of improperly, rather than in regulated landfills. This is also a reinforced feedback loop.

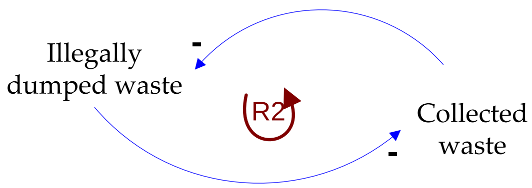

Figure 5.13: Positive feedback loop R2

In Figure 5.14, the variable *managers' incentive to implement waste management* will reinforce itself through the feedback loop R3. Firstly, an increase in managers' incentive to conduct waste management will result in more waste to be collected, which correspondingly leads to more waste to be sorted. When more waste is sorted, more waste can be reused. Subsequently, a larger amount of construction materials can be saved through waste reuse, which brings more benefits by managing C&D waste. An increased benefit of waste management indicates more net benefits will be gained from implementing waste management, which finally intensifies managers' incentive to carry out waste management.

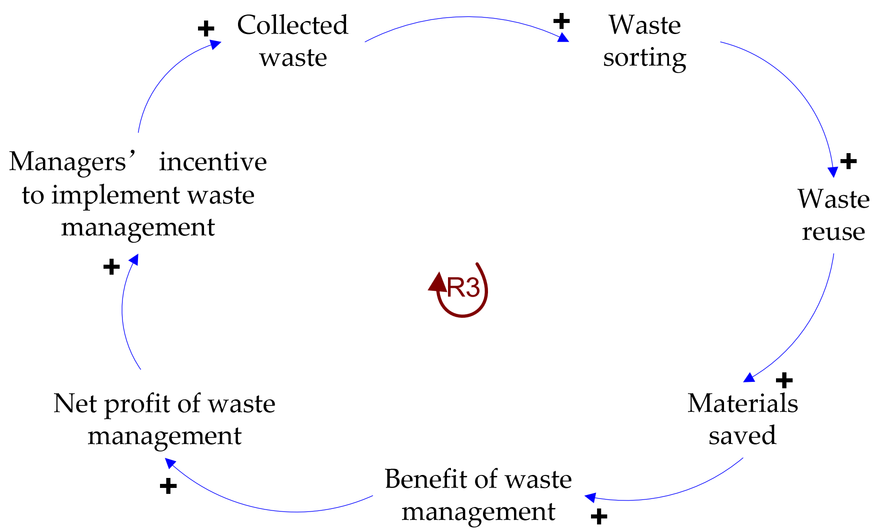

Figure 5.14: Positive feedback loop R3

In the feedback loop B1 which is shown in Figure 5.15, the variable *effort to reduce C&D waste* affects itself through a balanced feedback loop. More efforts devoted to C&D waste reduction result in a smaller amount of waste generation in the construction project. Less waste generation means that less waste can be collected. Similarly, the smaller volume of collected waste will lead to less waste to be sorted. Consequently, less effort will be needed to minimize C&D waste.

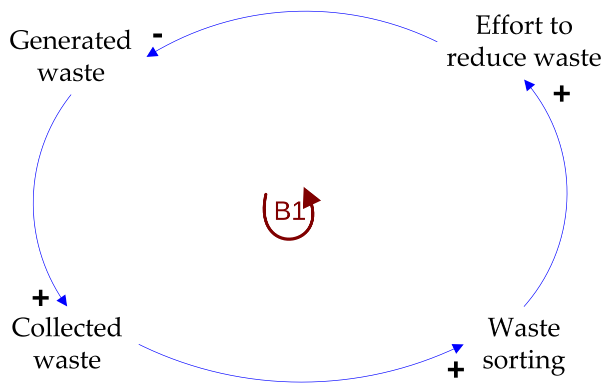

Figure 5.15: Negative feedback loop B1

In feedback loop B2 (see Figure 5.16), an increase in managers' incentive to implement waste management will cause more waste to be collected, and thereby increasing the cost required for waste collection. The increased cost of waste collection will then increase the total cost of waste management. Finally, the increased total cost of waste management will undermine managers' incentive to conduct waste management in the project. Hence, B2 is a negative feedback loop.

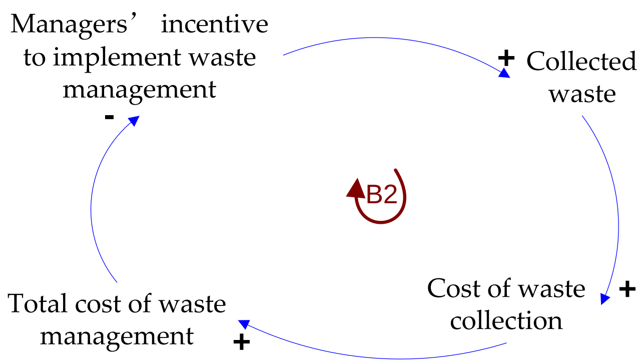

Figure 5.16: Negative feedback loop B2

The interrelationships of feedback loop B3 (see Figure 5.17) are similar to those in feedback loop B2. The only difference is that causal loop B2 is related to waste collection, while B3 is associated with waste sorting.

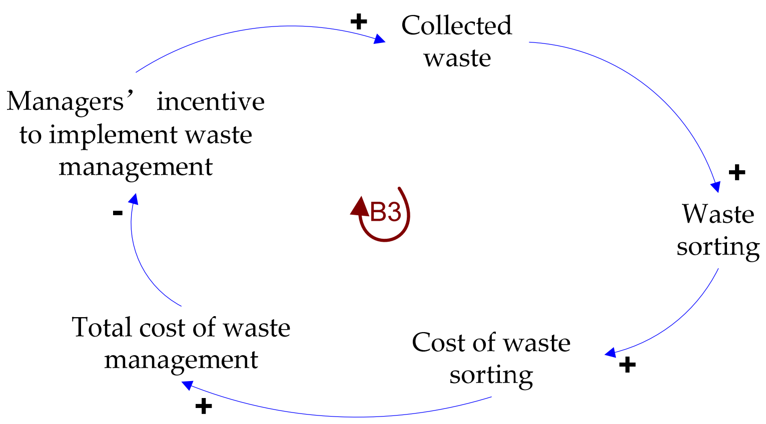

Figure 5.17: Negative feedback loop B3

The interrelationships of feedback loop B4 (see Figure 5.18) is similar to those in B2 and B3. It is a negative feedback loop and mainly concerns the cost of waste recycling and its impacts on managers' incentive to implement C&D waste management.

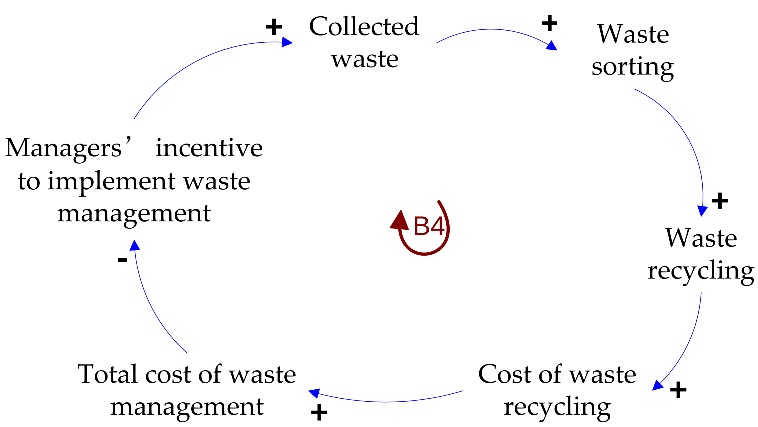

Figure 5.18: Negative feedback loop B4

Feedback loop B5, as shown in Figure 5.19, involves six variables that will have a negative influence on managers' incentive to implement waste management. Suppose that there is an increase in managers' incentive, the collected waste and waste to be sorted will both as a result increase. Then it is anticipated that the amount of waste transported from the construction site to landfills will increase and thereby increasing the total cost of waste management. At the end, the increased cost of waste management will weaken managers' incentive to implement waste management.

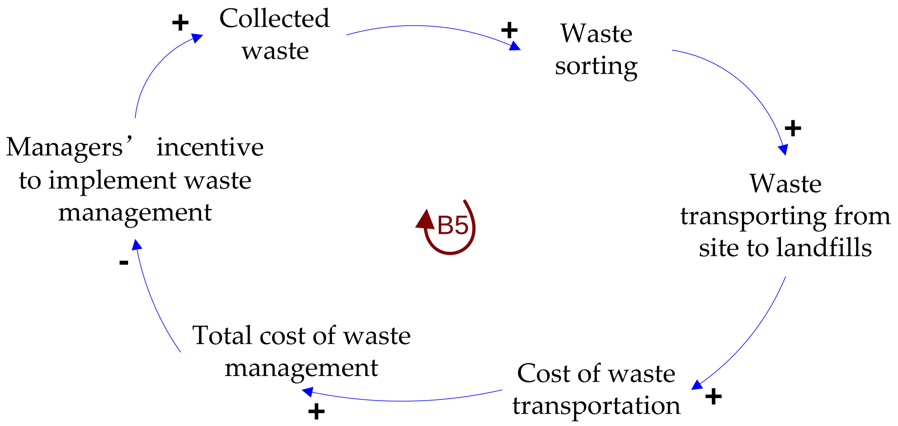

Figure 5.19: Negative feedback loop B5

By adding two variables – *waste disposed of at landfills* and *cost of waste disposal* – to negative feedback loop B5, a new feedback loop B6 (see Figure 5.20) can be formulated. In B6, an increase in managers' incentive to implement waste management will lead to an increased amount of waste disposed of at landfills. More waste entering landfills will result in a higher cost for waste disposal and undoubtedly raise the total cost of waste management. Consequently, managers' incentive to conduce waste management will be attenuated.

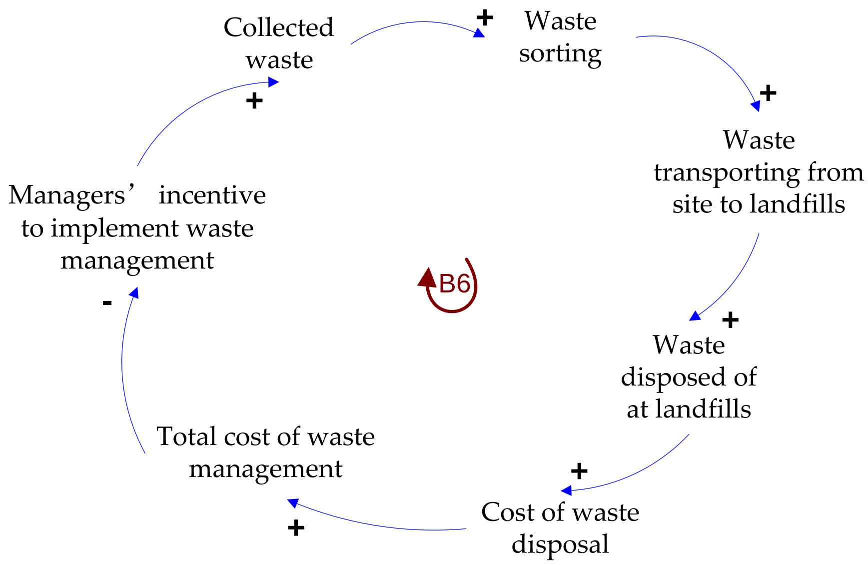

Figure 5.20: Negative feedback loop B6

In feedback loop B7 (see Figure 5.21), any variable (such as *managers' incentive to implement waste management*) will affect itself in a negative way through a series of feedback loops. For example, an improvement in managers' incentive to implement waste management will raise the amount of waste to be collected and subsequently leads to more waste to be sorted and reused. Then the total cost of waste management will be augmented due to the increased cost of waste reuse. Finally managers' incentive will be undermined due to decreased net profit of implementing waste management.

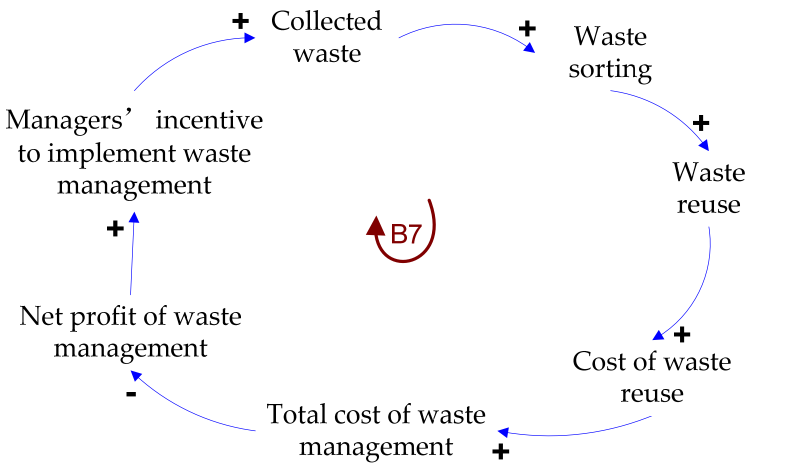

Figure 5.21: Negative feedback loop B7

The feedback loop B8 (see Figure 5.22) is to some extent similar to the feedback loop B2 of this subsystem. In feedback loop B2, the total cost of waste management influences managers' incentive to implement waste management directly. In feedback loop B8, however, the total cost of waste management firstly influences the net profit of waste management negatively, and finally managers' incentive to implement waste management will be positively affected by the net profit of waste management.

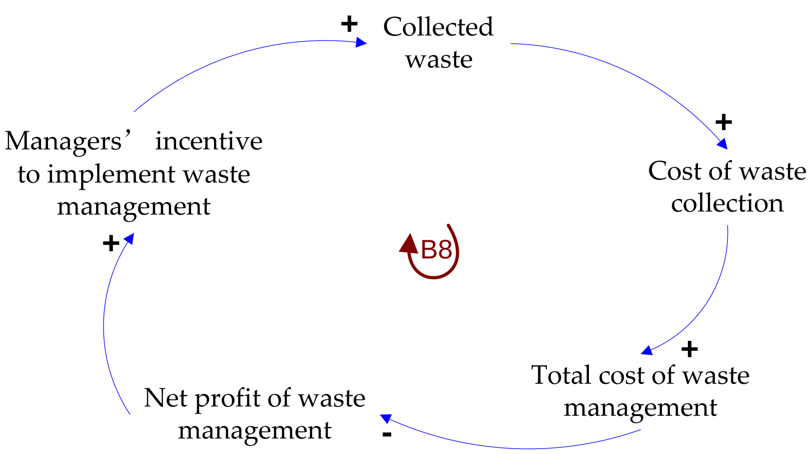

Figure 5.22: Negative feedback loop B8

Similarly, by adding the variable *net profit of C&D waste management* to the feedback loops B3, B4, B5, B6 and B7, feedback loops B9, B10, B11, B12 and B13 can be formulated respectively. Since these feedback loops can be observed, depicted and understood with easy by referring to Figure 5.17, Figure 5.18, Figure 5.19, Figure 5.20 and Figure 5.21, this section does not detail the illustration and explanation of these feedback loops.

5.4.3 Subsystem of environmental performance

It has been discussed in Chapter 3 that there are five variables influencing environmental performance of C&D waste management, including land consumption due to waste landfilling, water pollution, noise emission, air pollution, and environmental impacts of illegal waste dumping on public living environment. By constructing these variables in line with their interrelationships, the causal loop diagram of the subsystem of environmental performance which involves five feedback loops in total is formed (Figure 5.23). Among the feedback loops, two are positive (R1 and R2) and the other three are negative (B1, B2 and B3).

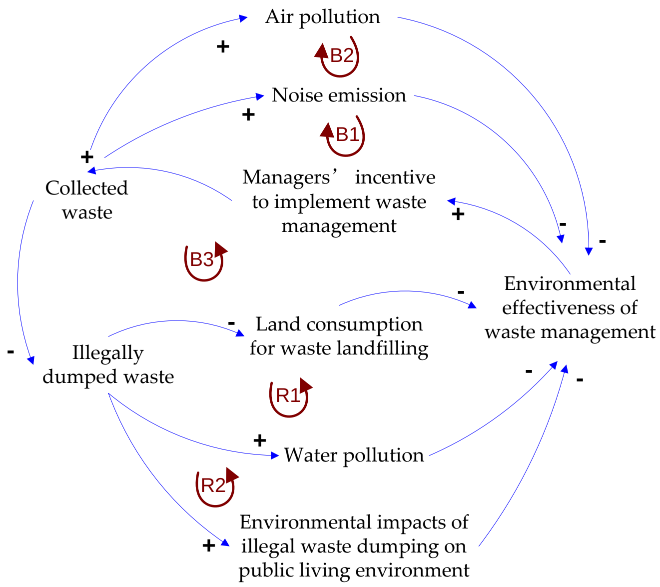

Figure 5.23: Causal loop diagram of the environmental performance subsystem

It is noted from feedback loop R1 (see Figure 5.24) that a change in any variable within the causal loop will eventually affect itself positively. For example, an improvement in managers' incentive to implement waste management will raise the amount of collected waste, which then decreases the amount of illegally dumped waste. Afterwards, the less illegally dumped waste will cause less pollution to water, and then less water pollution indicates a more effective environmental performance of waste management. At the end, the higher environmental effectiveness of waste management will stimulate managers' incentive to conduct C&D waste management.

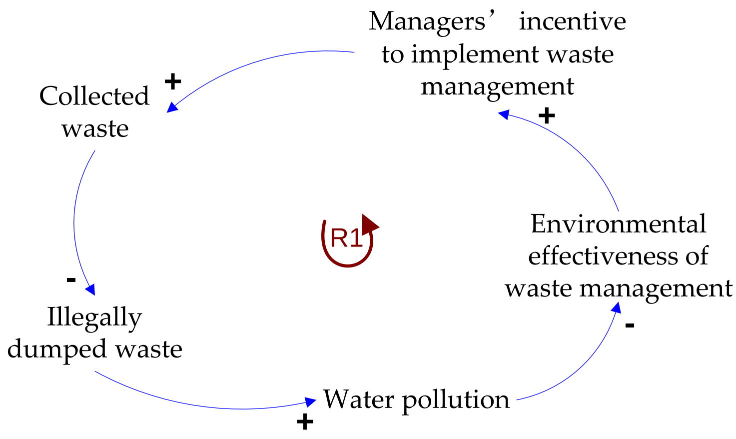

Figure 5.24: Positive feedback loop R1

By replacing the variable *water pollution* with the variable of *environmental impacts of illegal waste dumping on the public living environment* in feedback loop R1, a new feedback loop R2 can be developed, as shown in Figure 5.25. The causal relationships among R2 are similar to those in loop R1.

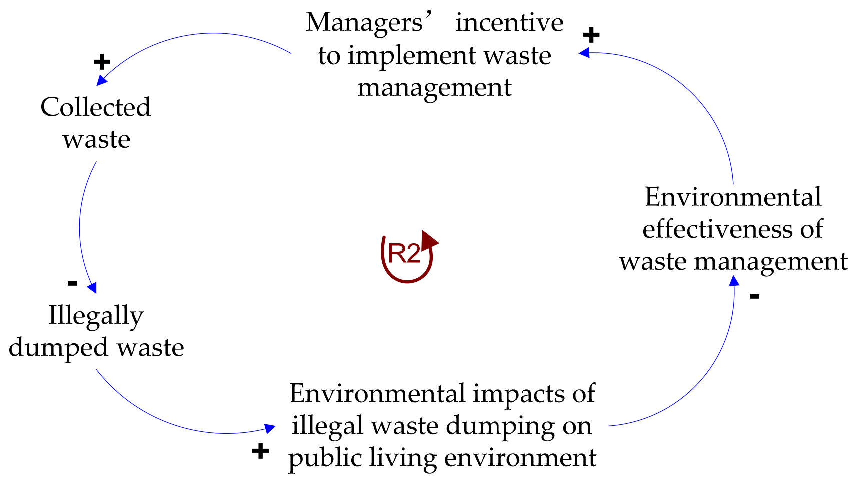

Figure 5.25: Positive feedback loop R2

Feedback loop B1, as demonstrated in Figure 5.26, contains four variables. A change on any variable will affect itself in a negative way. For instance, a larger amount of collected waste will cause more noise emission during the waste collection process. More noise emission indicates a lower environmental effectiveness of waste management, which to some extent reduces managers' incentive to implement waste management. Eventually, the lower incentive to conduct waste management will lead to a smaller volume of C&D waste to be collected in the project.

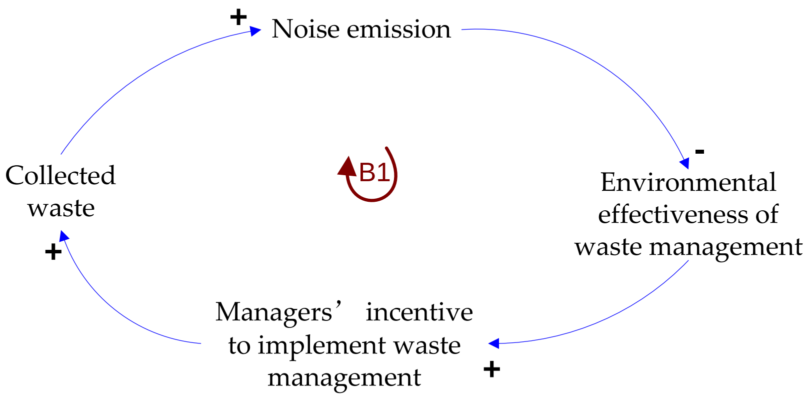

Figure 5.26: Negative feedback loop B1

Feedback loop B2 (see Figure 5.27) has similar causal relationships as the feedback loop B1, while the only difference is to replace the variable of *noise emission* with the variable of *air pollution*. It depicts how impacts of air pollution influence the environmental effectiveness of C&D waste management.

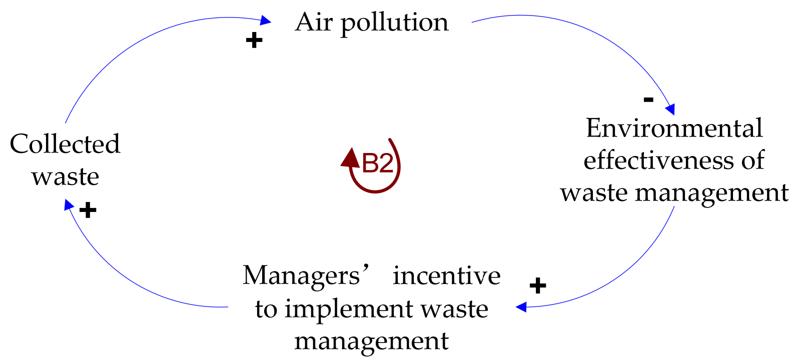

Figure 5.27: Negative feedback loop B2

The feedback loop B3 shown in Figure 5.28 is also negative. In this causal loop, an increase in managers' incentive to implement waste management will contribute to waste collection and results in more collected waste. As a consequence, a smaller amount of waste will be illegally dumped, which implies more land resources will be occupied for C&D waste landfilling. Afterwards, more land consumption for waste landfilling leads to a lower environmental effectiveness of waste management. Finally, the lower environmental effectiveness will undermine managers' incentive to conduct waste management.

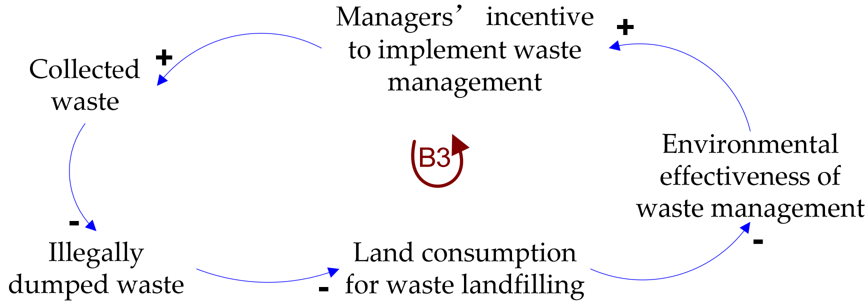

Figure 5.28: Negative feedback loop B3

5.4.4 Subsystem of social performance

It has been discussed in Chapter 3 that there are eight variables affecting social performance of C&D waste management, including practitioners' awareness to manage waste, provision of job opportunities, physical working condition, impacts on long-term health, safety of workers in conducting C&D waste management, public satisfaction about C&D waste management, impacts of illegal waste dumping on the social image, and public appeal for regulating illegal waste dumping. By building these variables based on their interrelationships, the causal loop diagram of the subsystem of social performance which contains six feedback loops in total is established (Figure 5.29). Among the feedback loops, one is negative (i.e. B1) and the other five are positive (i.e. R1, R2, R3, R4 and R5). The behavior of the whole system is determined through the dynamic interactions of these feedback loops.

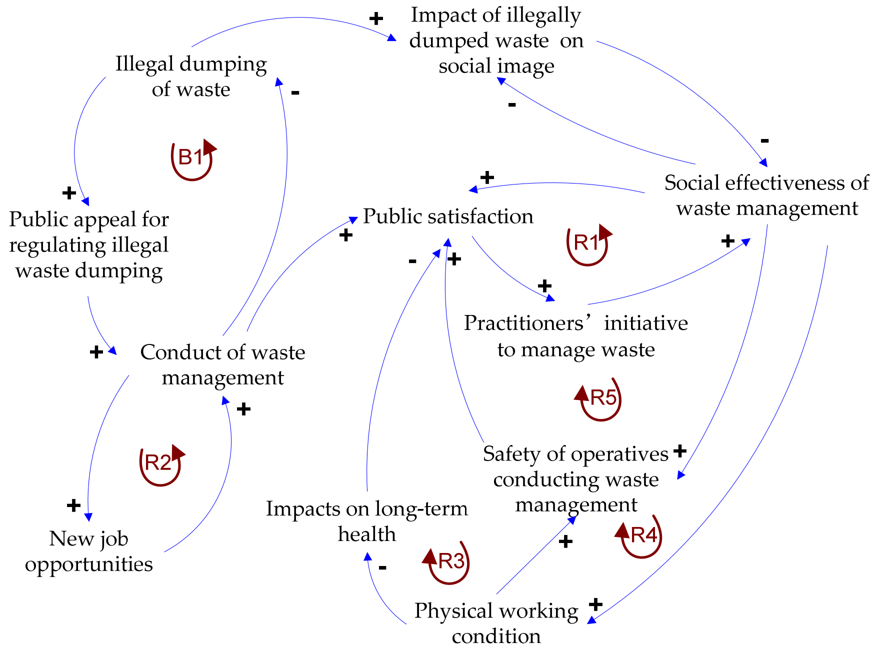

Figure 5.29: Causal loop diagram of the social performance subsystem

By referring to feedback loop B1 (see Figure 5.30), it can be seen that a larger amount of waste dumped illegally will raise the public appeal for regulating illegal waste dumping behavior, which enhances the conduct of waste management. The amount of waste dumped illegally will finally be minimized to some extent due to the enhancement of waste management.

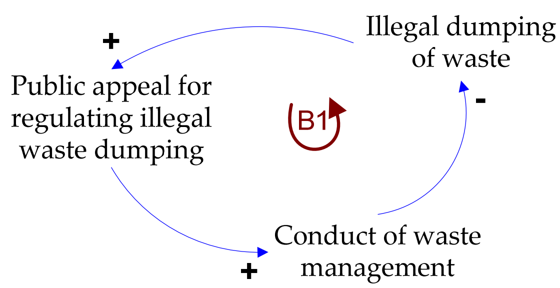

Figure 5.30: Negative feedback loop B1

In the positive feedback loop R1 (see Figure 5.31), a change on any variable will affect itself in a reinforced way. For example, an increase in practitioners' initiative to manage waste will contribute to the social effectiveness of waste management. The higher social effectiveness of waste management will then increase public satisfaction about waste management, which at last stimulates practitioners' initiative to manage waste. This means that an increase in practitioners' initiative to manage waste will lead to an improvement in public satisfaction about waste management.

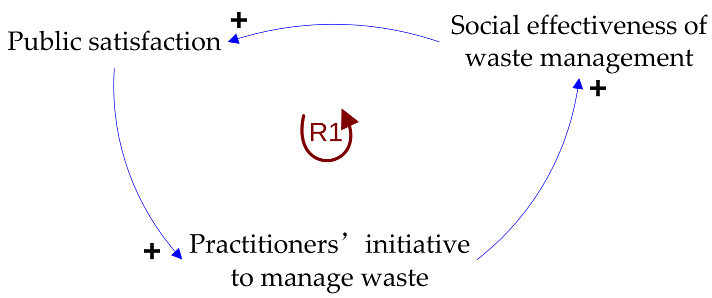

Figure 5.31: Positive feedback loop R1

Feedback loop R2 shown in Figure 5.32 describes the interrelationships between *new job opportunities* and *conduct of waste management*. On one hand, the implementation of C&D waste management provides more new job opportunities for the entire society; on the other hand, the employment of more people for the work can in turn better facilitate the conduct of C&D waste management.

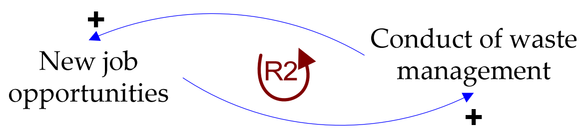

Figure 5.32: Positive feedback loop R2

In the positive feedback loop R3 (see Figure 5.33), it can be observed that the physical working condition will influence impacts of waste management activities on the long-term health of practitioners involved. Better physical working condition will make the workers suffer fewer impacts on their long-term health. If practitioners have to work under a worse condition that brings adverse impacts to their long-term health, the public satisfaction about waste management will be relatively lower. Then the public satisfaction will affect practitioners' initiative to manage waste positively; that is, if the public satisfaction is higher, practitioners will be more active in engaging in waste management activities. The increase in practitioners' initiative to manage waste can help improve the social effectiveness of waste management. Consequently, the higher social effectiveness of waste management contributes to a better working condition for performing waste management.

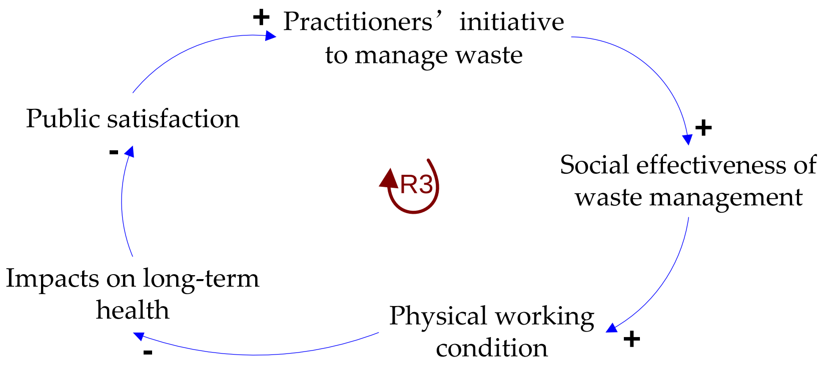

Figure 5.33: Positive feedback loop R3

Some of the causal loop relationships in feedback loop R4 (Figure 5.34) are the same as R3, the difference is that physical working condition will affect the safety of operatives in waste management, and then the safety of operatives will contribute to the public satisfaction about waste management. A change on any variable within this causal loop will influence itself positively.

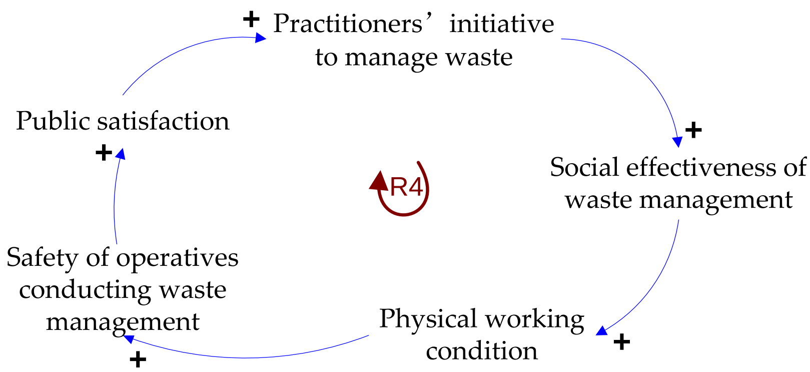

Figure 5.34: Positive feedback loop R4

Figure 5.35 is an illustration of feedback loop R5 of the subsystem. In this causal loop, the behavior of the feedback loop will be reinforced by a change on any variable. For example, an improvement in the safety of operatives will promote the public satisfaction with C&D waste management, which then contributes to practitioners' initiative to manage waste. Afterwards, a higher social effectiveness of waste management can be achieved through the enhancement of practitioners' initiative. Finally, the higher social effectiveness contributes to a safer environment for operatives to implement waste management.

Figure 5.35: Positive feedback loop R5

5.5 Stock-flow diagram

Having identified the causal loop relationships between the variables, as discussed in Section 5.4, it is necessary to build a stock-flow diagram based on these loop relations so that the model can run on a computer. In fact, the causal loop diagram and the stock-flow diagram are simply two different versions of the same model. The difference is that the former is written in arrows and words, and constructed in the hope of understanding the problem better; the latter is in equations and computer code, which allows us to simulate the model and carry out quantitative analysis (Coyle, 1996). Based on the causal loop diagrams described in Section 5.4, the stock-flow diagram for examining the effectiveness of C&D waste management can be constructed, as shown in Figure 5.36. The definitions of all individual variables involved in Figure 5.36 are detailed in Appendix A.

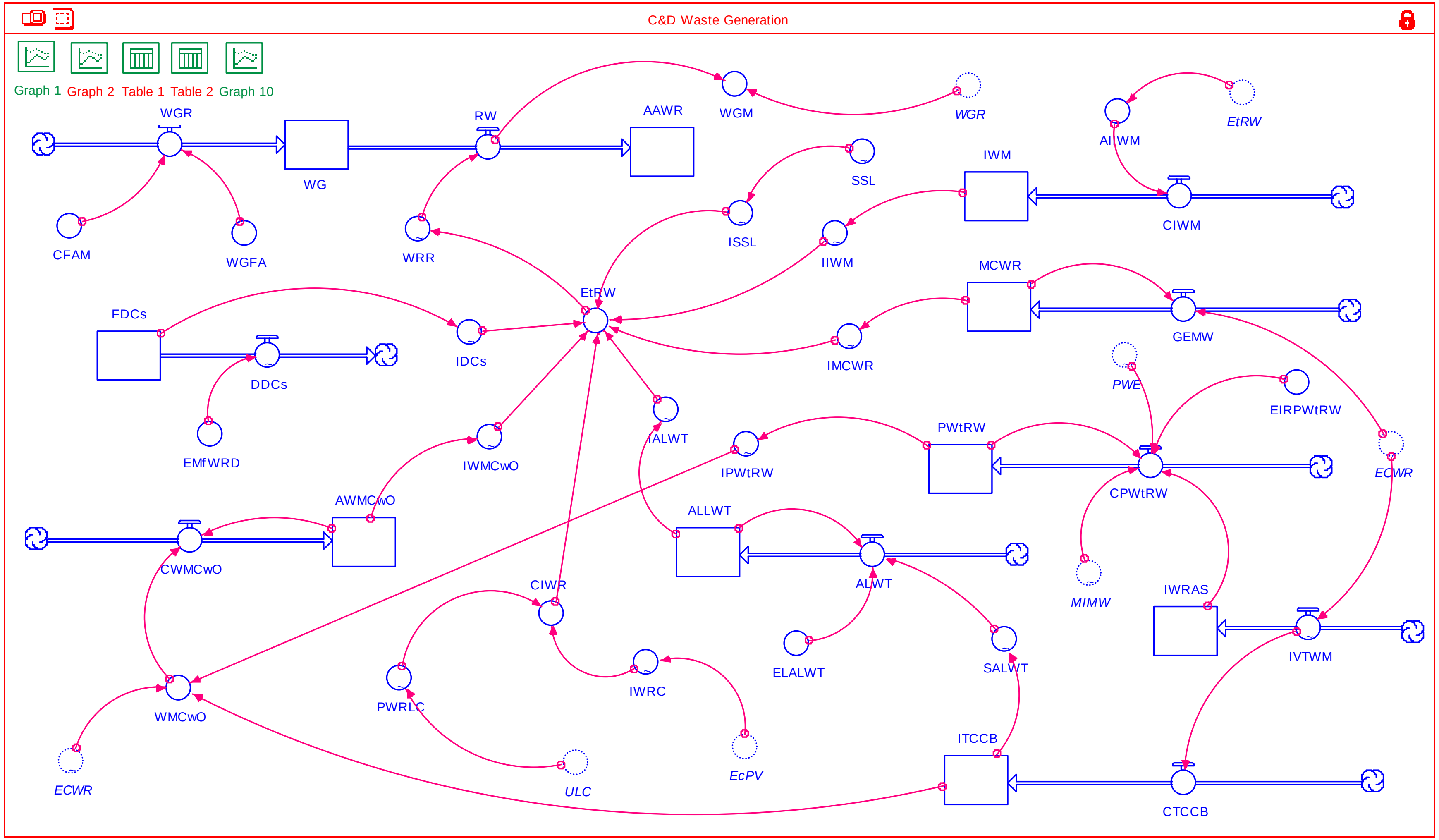

Figure 5.36: A model for examining the effectiveness of C&D waste management

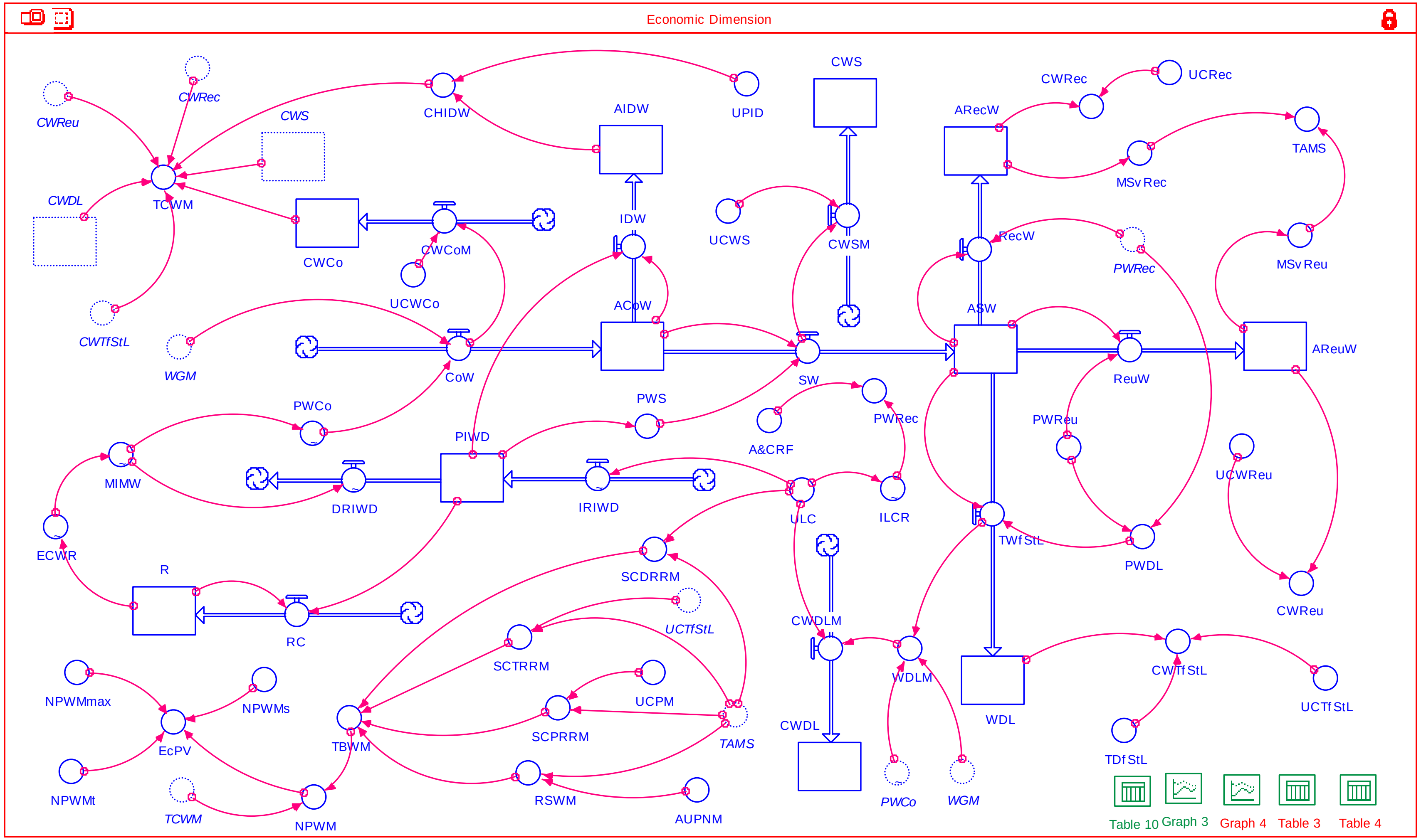

Figure 5.36: A model for examining the effectiveness of C&D waste management (con't)

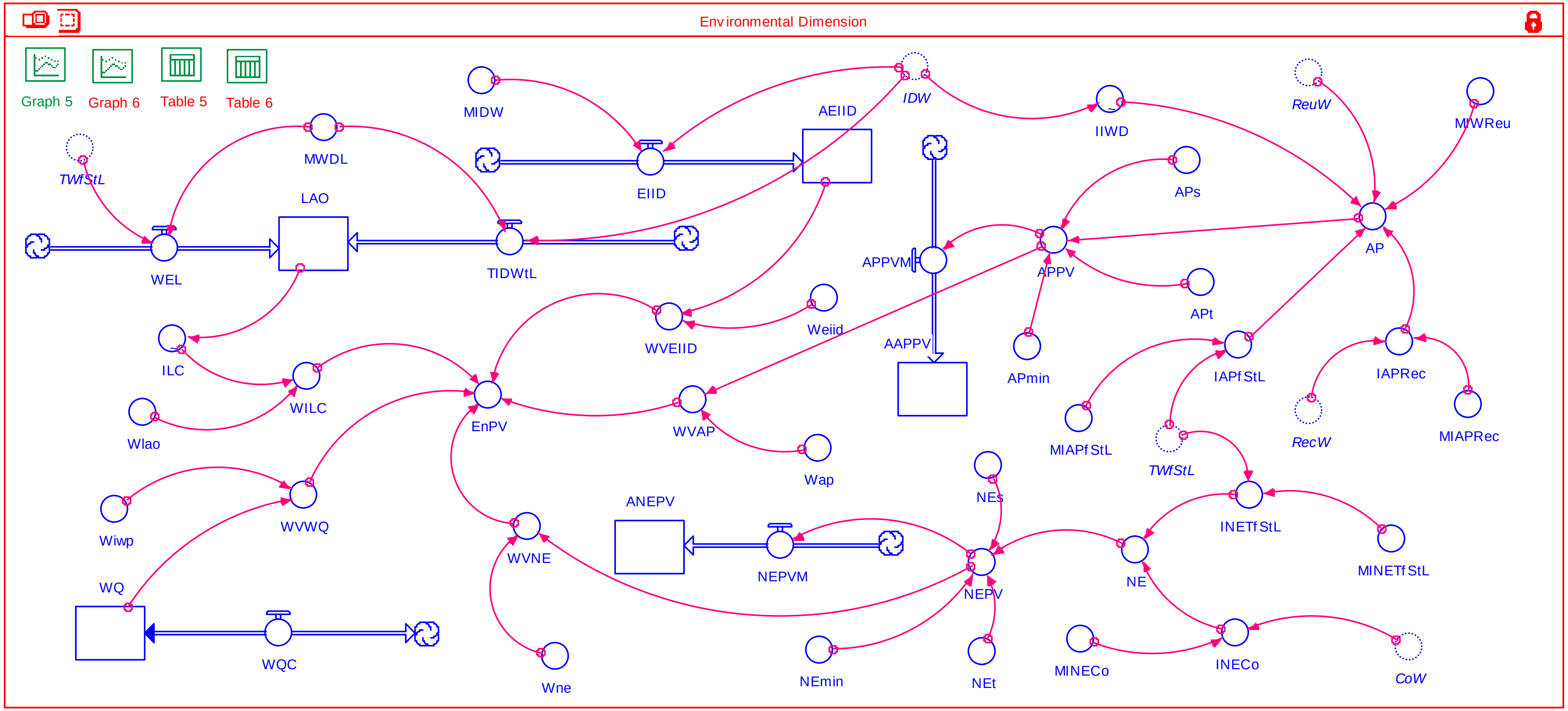

Figure 5.36: A model for examining the effectiveness of C&D waste management (con't)

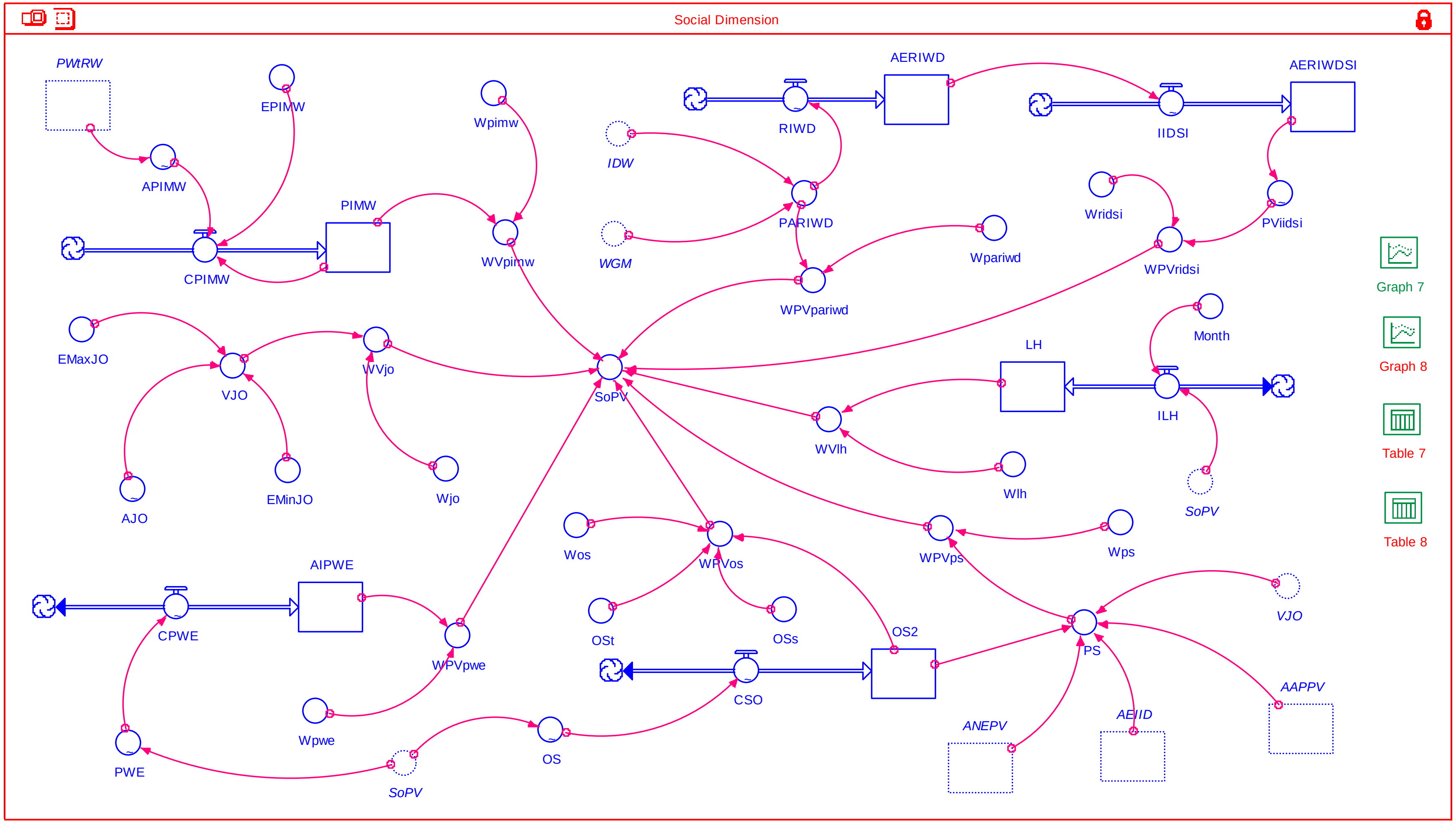

Figure 5.36: A model for examining the effectiveness of C&D waste management (con't)

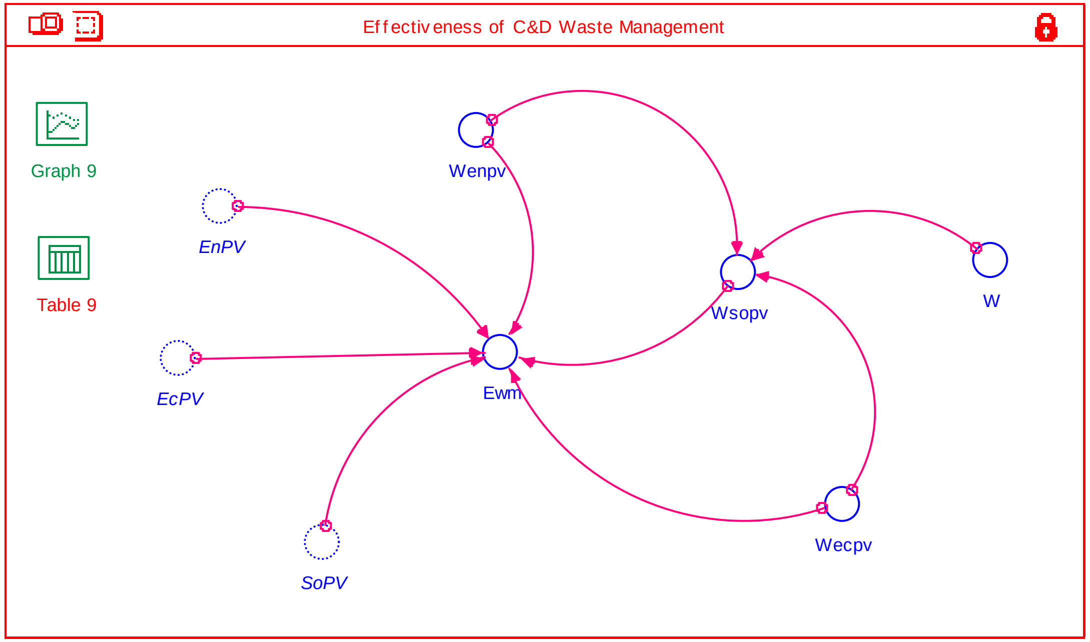

Figure 5.36: A model for examining the effectiveness of C&D waste management (con't)

It is important to note that the five subsystems are connected through certain variables. For the sake of understanding, Figure 5.37 depicts clearly how these subsystems are inter-linked and what are the common variables that connect each pair of subsystems.

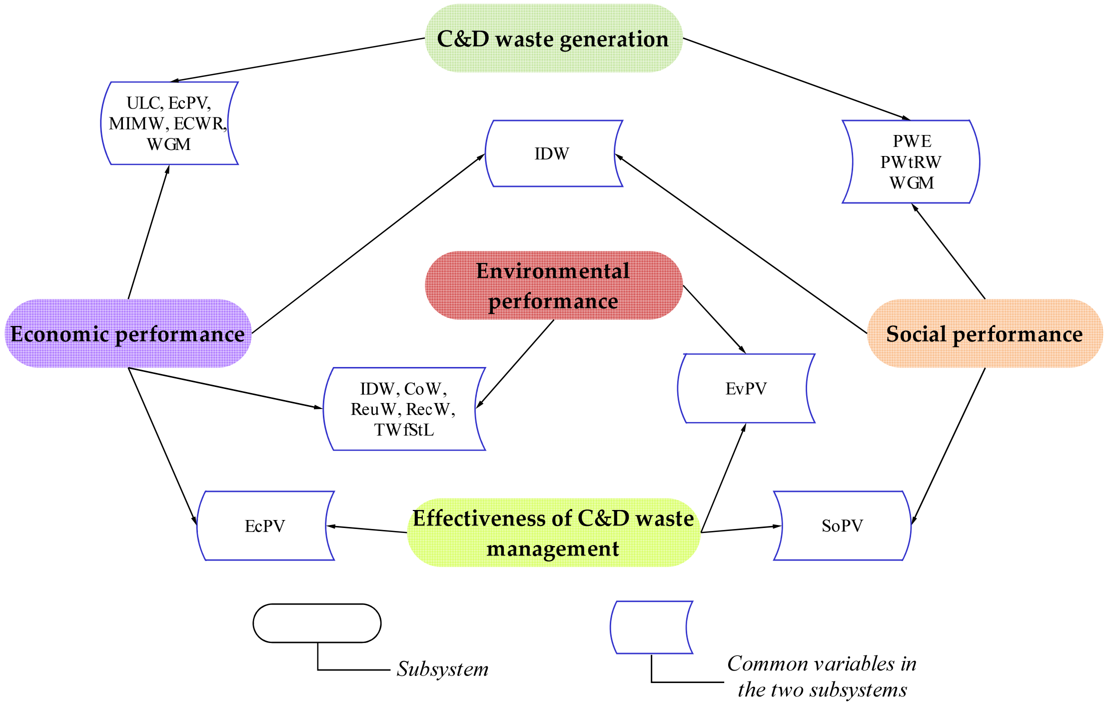

Figure 5.37: The interrelationships among the five sub-systems

As can be seen in Figure 5.37, most of the subsystems are mutually connected through some common variables. For example, subsystem of 'C&D waste generation' is related to 'economic performance' with common variables of ULC, EcPV, MIMW, ECWR and WGM. 'C&D waste generation' is also connected with 'social performance' through variables of PWE, PWtRW and WGM. The common variables shared by any two subsystems allow better comprehension of the feedback effects underlying the two subsystems. In this way, all the five subsystems can be organically incorporated into a system for evaluating the effectiveness of C&D waste management.

5.6 Summary

This chapter presented a step-by-step account of the development of the dynamic model for assessing the effectiveness of a C&D waste management system. It also provided a detailed explanation on how the variables included in the subsystems inter-relate with each other through a series of causal loop diagrams. At the end of the chapter, a dynamic model in the form of stock-flow diagram was established with the aid of the software iThink.

The next chapter carries out a real case study in using the SD model developed in this Chapter. It will show how the dynamic model was tested and validated by illustrating how it mirrors the real-world situations. Sensitivity analysis, as a part of the validation process, is also demonstrated to show that how the model responds under varying conditions over the C&D waste chain.

CHAPTER 6 Application of the SD-based C&D Waste Management Effectiveness Assessment Model: A Case Study

6.1 Introduction

The previous chapter provided an exhaustive description of how a dynamic model for assessing the effectiveness of C&D waste management was built and visualized by using causal loop diagrams and stock-flow diagrams. The model was designed as a tool for better assessing the effectiveness of C&D waste management and further function as a platform for simulating the effects of different management policies. This chapter therefore mainly concentrates on the illustration of model application by using data collected from a construction project in China. The main purpose of applying the model to a real project was to build confidence in the model so that it could be used as an experimental platform for further analyses.

This chapter starts with a brief overview of the C&D waste management situation in China, which is helpful for readers to acquire an understanding of the particular background on which the case study is based. Then it moves on to an introduction to the selected case. Using the dynamic model previously developed, the case study was then conducted in three stages. The first stage was to interpret how different types of variables in the model are quantified through appropriate methods. The second stage was to validate the applicability of the model by detailing different tests required by the SD approach. The third stage was to simulate the base run of the model and analyze the simulation results accordingly.

6.2 An overview of C&D waste management practice in China

The author of the C&D waste management effectiveness assessment model aims for promoting the application of the model to improve the effectiveness of C&D waste management in general. However, there is a need for a particular practice to help validate the model. The construction practice in China was chosen for this purpose in this study. China is considered representative as C&D waste has been a major source of solid waste generation. For example, it was estimated that in 2008, China produced 29% of the world's MSW, of which construction activities contributed nearly 40% (Wang et al., 2008). On the other hand, C& D waste in China has not been well processed and presented serious problems to the development of the Chinese construction industry, thus it is considered significant and adequate to choose a case study in China.

Over the past thirty years, China has enjoyed exceptionally rapid economic growth, achieving a GDP growth of up to 9.8% annually (NBS, 2007). However, in parallel with this impressive economic development has been a severe degradation of China's environment caused in part by the large amount of waste generated by construction activities associated with expanding urbanization and infrastructure projects. Dong et al. (2001) found that China produced approximately 30% of the world's MSW, and more recently Wang et al. (2008) found that amongst China's MSW, construction activities were responsible for nearly 40%, having consumed about 40% of total natural resources and around 40% of energy.

C&D waste management in China came into focus in the 1990s when China sped up its economic reforms and the environmental degradation caused by the consequential increased manufacturing and construction activities reached an alarming point. This led to the promulgation of many laws and regulations such as the *Environment Law of the People's Republic of China (P.R.C.)* (1989), the *Law of the P.R.C. on Prevention of Environmental Pollution Caused by Solid Waste* (1995, revised 2004), *Regulations on the Urban Environmental Sanitation Management* (1992), and the *Administrative Measures for Urban Living Waste* (2007), that placed C&D waste management under scrutiny and promoted its practice.

Studies over the past fifteen years have provided a better understanding of C&D waste management. For example, Zhang et al. (1995) investigated the practice and benefits of construction waste reduction on-site. Li et al. (1999 and 2001) examined C&D waste reuse technology and investigated the measures for C&D waste management through site investigation. Wang et al. (2004b) analyzed the major factors affecting the generation of C&D waste in different regions, while Wang and Yuan (2008) attempted to deal with the complexity of on-site waste management by using a system dynamics approach. Research has also revealed the problems associated with waste management including the use of traditional construction techniques and a lack of sufficient waste management skills (Wang and Yuan, 2006), a lack of incentives for implementing C&D waste reduction on-site (Wang and Yuan, 2008), and a lack of government rules on waste management along with relatively low landfill charges in China (Yuan, 2008).

The latest situation in China evidences that the majority of C&D waste has not been well processed, which has caused heavy ecological damage and environmental pollution. Environmental issues have received increasing attention, but currently the level of expertise and application of good waste management in China's construction sector is not sufficient. Reasons for poor C&D waste management in China are many, including no practical regulations that companies can follow, lack of C&D waste management system within companies, and no incentive schemes. It is considered that C&D waste management is complex, involving not only technical (e.g. low-waste construction technologies), but also managerial and economic issues (e.g. C&D waste management system and C&D waste trade scheme). In addition, effective waste management cannot be achieved without efforts from all stakeholders including government, clients, designers, contractors, suppliers and the general public. Improving C&D waste management in China should start with a better understanding of its multidisciplinary nature and involve active participation from all stakeholders. However, no systematic research has been conducted to investigate effective C&D waste management in China. This further highlights the pressing need to conduct substantial research into effective management of C&D waste in China's fast developing construction sector.

Particularly, the model developed for this study was validated and its application demonstrated by using it to investigate a C&D waste management case in Shenzhen, which is a coastal city located in southern China adjacent to Hong Kong. It was established as a Special Economic Zone (SEZ) in 1980 under China's 'open door' policy. For many years before China officially adopted a market economy, Shenzhen was the experimental zone for China's economic reforms. During the past two decades, Shenzhen's economy has developed rapidly transforming it from a small fishing village into a modern 1,952 km^2 city with a population of around 8.46 million. In 2008, Shenzhen's GDP was about 780.65 billion Yuan (US$114.30 billion) with the value of the construction sector accounting for 19.75 billion Yuan (US$2.89 billion) or 2.5% of that value (NBS, 2009).

The large-scale construction activities that have occurred in Shenzhen region over the past few years have produced an overwhelming amount of C&D waste in the region. According to the Shenzhen Environmental Department, the total volume of C&D waste generated in 2005 was around 6 million tons, which is an average of about 17,000 tons per day (Li, 2006). Therefore, the findings of the model are expected to give insights into strategies for systematically improving the C&D waste management practice in Shenzhen. The findings might also applicable to other regions in China facing similar problems.

6.3 Background of the selected case

The dynamic model was constructed according to qualitative analyses of relationships between interrelated variables. To enable quantitative analysis, an appropriate value for each variable should be assigned. This was performed by a case study carried out in the construction industry of Shenzhen, South China.

The data collection was conducted during the period of June 1 and July 31, 2010. The project selected is a new frame-structured public building, which is located in the Nan'shan district of Shenzhen. The gross floor area is 47,000m^2 and the total investment amounts to 104 million Yuan (US$15.6 million). The building height is 44 meters with 9 stories above ground and 1 story underground. The construction duration of the project is 18 months. A group of pictures exhibiting a glimpse of C&D waste practice in this project is shown in Figure 6.1.

Figure 6.1: A glimpse of C&D waste practice in the selected project

Data were mainly collected through two channels. One was the site survey consisting of a series of formal and informal meetings and communication with five on-site staff, including one project manager, one on-site manager, one on-site technical engineer and two supervision engineers. These experts were selected due to their extensive experience in construction management, including C&D waste management. As the main stakeholders, they play a key role in launching and implementing C&D waste management policies. Detailed profile of these experts is tabulated in Table 6.1. The other data collection channel was through interviews and consultation with eight inhabitants living nearby. The justification for involving inhabitants in the neighborhood is due to that fact that the model is concerned with several variables associated with the social impact of C&D waste management activities.

Table 6.1: Profile of the experts consulted in the case

No.	Title	Affiliation	Experience in construction management
1	Project manager	Contractor	17 years (12)
2	Site manager	Contractor	13 years (11)
3	Site technical engineer	Contractor	14 years (6)
4	Chief supervisory engineer	Supervisory company	19 years (16)
5	Supervisory engineer	Supervisory company	11 years (11)

Note: Figures in blanket indicate years of experience involved in C&D waste management.

The project was at the stage of constructing the sixth floor when the case study was carried out. The project had implemented measures for dealing with the C&D waste generated on-site. For example, the project implemented the ISO14000 environmental management standard and based on the standard, a detailed 'On-site environmental management specifications' was launched as well. It is introduced that the on-site environmental management specifications provided guidelines on how to minimize pollution caused by construction activities, including C&D waste management activities. Also, on-site waste sorting was conducted in the project; particularly, the C&D waste was collected and sorted into three categories, including hazardous waste, recyclable or reusable waste, and waste that can not be recycled or reused. The hazardous waste was handled by certified solid waste processing companies. Some waste materials were collected and sorted for direct reuse; for example, the waste timber was used as fuel in the project canteen. The waste that can not be recycled or reused was sent to landfills for disposal.

6.4 Methods for quantification of variables

Prior to performing the simulation, it is essential to ensure the adequacy of the data inputs for all variables involved in the model. The variables contributing to the effectiveness of a C&D waste management system have been addressed in Chapter 3 and built into the SD model in Chapter 5. These variables are in three categories, namely, quantitative, qualitative and dependent, and each should have its own data source.

Some variables are *quantitative variables (constant parameters).* Values of constant parameters will remain during the whole period of simulation. Variables of this kind can purely affect other variables in the system but not bear the influence exerted by other variables. For example, ULC (unit landfilling charge) is a constant parameter. It can affect variables including PWRec, IRIWD and SCDRRM (referring to Figure 5.36) but will not be influenced by any of the variables contained in the system. Values of constant parameters (such as ULC) can be obtained by referring to information and records of the project under study, previous research papers, reports or governmental regulations (Method for quantification: M1).

Another stream of variables can be denominated as *dependent variables*. The value of a dependent variable is determined by those of one or more other variables in a function. Therefore, a dependent variable needs to be represented by describing its interrelationship with other variables. Fortunately, the iThink software has a noteworthy advantage which provides 'Graphical' function for illustrating the interrelationship between any two variables. This function of the software enables effective and good descriptions of dependent variables (Quantification method: M2). An example of the dependent variable is PWRLC (promotion of C&D waste reduction via landfilling charge) in the sub-system of C&D waste generation. This variable is affected by a constant variable ULC (unit landfilling charge), which indicates that the value of PWRLC will vary in line with any alteration in ULC. In the model, their relationship is portrayed as in Figure 6.2.

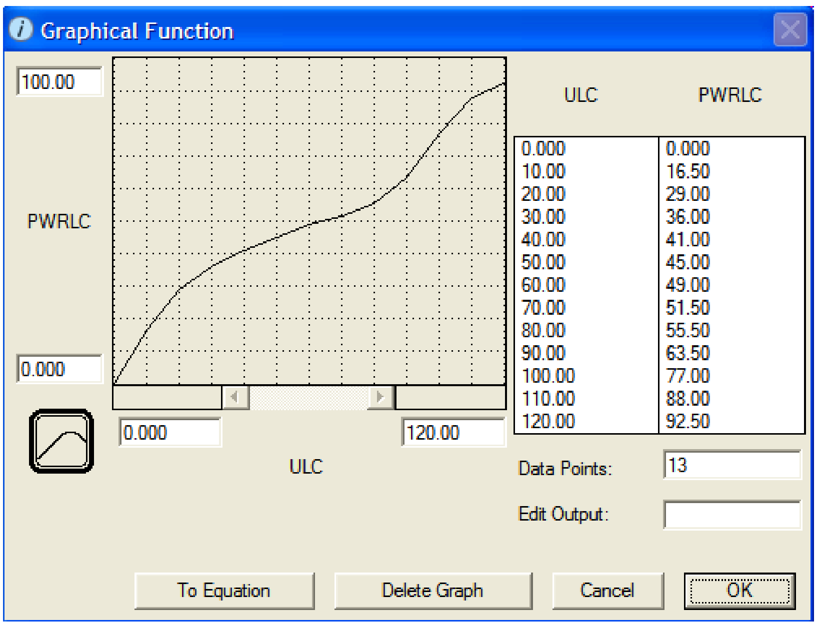

Figure 6.2: The relationship between PWRLC and ULC

In Figure 6.2, the value of ULC can change across a wide range from 0 to 120 Yuan per ton and PWRLC can range from 0 to 100. Through observing the curve, it is easy to see that PWRLC will vary from 0 to 92.5 in line with the variation of ULC from 0 to 120; for example, if the local government launches a waste landfilling charge of 50 Yuan per ton, it would promote the effect of C&D waste reduction to the level of 45.

The last type of parameters is *qualitative variables*. Values of qualitative variables can only be obtained through survey, such as questionnaire, interview, on-site visit, etc. It has been found that a large amount of variables involved in the model are qualitative. They should be quantified before the model can be simulated. Quantification of qualitative variables in this study is performed using five methods, which are introduced as follows.

The first method (M3): For some qualitative variables, for example, 'NE - noise emission', which limits are set in documents such as bidding materials, governmental legislation and guidelines, etc., the principle of measuring the performance of these variables is to pursue smaller values. Their performance values can be calculated using the following formula (Qiu, 1991):

$$P_i = \begin{cases} 100 & x \le x_{\min} \\ (\dfrac{x - x_s}{x_{\min} - x_s}) \times k + q & x_{\min} < x \le x_s \\ q \times (\dfrac{x - x_t}{x_s - x_t}) & x_s < x \le x_t \\ -100 & x > x_t \end{cases}$$

where P_i is the normalized performance value of a given variable, x is actual performance value of the variable, $x_{\min}$ is the minimal satisfaction value set by decision-makers reflecting the decision-maker's opinions and preference, x_s is the standard value required by the statutory documents, x_t is maximal tolerable value set by decision makers which may meet the statutory standard after applying some improvement measures and q is set to 60 which is a pass score and k is (100-q)

The second method (M4) is suitable for those qualitative variables, for example, 'land consumption due to C&D waste landfilling', which pursue the smaller value and have no limits regulated in statutory documents. Two reference points on the utilized scale are defined, corresponding to the best and worst performance that could realistically occur, and assigned values of 0 and 100 respectively. These variables are quantified by the following formula (Qiu, 1991):

$$P_i = (\frac{x - x_{\max}}{x_{\min} - x_{\max}}) \times 100$$

where P_i is the normalized performance value of a given variable, x is the actual performance value of the variable, $x_{\min}$ is the minimal performance value (best performance) set by decision-makers and x_{max} is the maximal performance value (worst performance) set by decision-makers.

The next method (M5) is used for those qualitative variables which pursue higher performance value and have the bottom limits required by the decision rules of an variable itself, such as 'EcPV - economic performance value', which is required to be equal to or greater than -100 when a decision is made, two reference points on the utilized scale are defined, corresponding to the satisfactory performance value, and basic standard and assigned values of -100 and 100 respectively. These variables are scored as follows (Qiu, 1991):

$$P_i = \begin{cases} 100 & x \geq x_{max} \\ (\frac{x - x_s}{x_{max} - x_s}) \times k + q & x_s \leq x < x_{max} \\ q \times (\frac{x - x_t}{x_s - x_t}) & x_t < x \leq x_s \\ -100 & x < x_t \end{cases}$$

where P_i is the normalized performance value of a given variable, x is the actual performance value of the variable, x_{max} is the maximal satisfaction value set by decision-makers, x_s is the basic standard required by the decision rules of the variable itself and x_t is the minimal tolerable value set by decision-makers which may meet the basic standards required by the decision rules of the variable itself after adopting some improvement measures. q is set to 60 which is a pass score and k is ($100-q$).

The fourth method (M6) is used for those variables which limits are not defined in statutory documents such as legislation, guidelines, etc. or in decision rules required by the variable itself and pursue the higher value, such as 'JO - job opportunities'. Two reference points on the utilized scale are defined, corresponding to the maximal performance value and minimal performance value and assigned values of 100 and 0 respectively. These variables are scored as follows (Qiu, 1991):

$$P_i = (\frac{x - x_{\min}}{x_{\max} - x_{\min}}) \times 100$$

where P_i is the normalized performance value of a given variable, x is the actual value of an variable, $x_{\min}$ is the minimal performance value set by decision-makers and $x_{\max}$ is the maximal performance value set by decision-makers.

The last method (M7) is adopted for the evaluation of qualitative indicators, for example, the variable 'SSL - limit of site space', a Likert-type scale structure is applied for evaluating the performance of this qualitative variable. A score ranging from 0 to 100 will be assigned to each qualitative variable by those with expert knowledge in the area wherever appropriate. This mechanism generates discrete scores, which are for example 100, 80, 60, 40, 20 and 0, for qualitative variables.

All the variables in the SD model (including constant, dependent and qualitative) and the specific methods for their quantification are summarized in Table 6.2.

Table 6.2: Data collection methods for major variables

Variables	Type	Methods for quantification	Subsystem
CFAM, WGFA, EMfWRD, ELALWT, EIRPWtRW	Quantitative	M1	C&D waste generation
WRR, IDCs, DDCs, IWMCwO, CWMCwO, PWRLC, IWRC, SALWT, IALWT, IPWtRW, IMCWR, ISSL, AIIWM, IIWM, IVTWM	Dependent	M2	
SSL	Qualitative	M7	
UPID, UCWCo, UCWS, ULC, UCReu, UCRey, A&CRF, UCTfStL, TDfStL, UCPM, AUPNM, NPWmax, NPWMs, NPWMt	Quantitative	M1	Economic performance
ECWR, MIMW, DRIWD, IRIWD, ILCR	Dependent	M2	
EcPV	Qualitative	M5	
MWDL, MIDW, Wlao, Wiwp, Wne, Wap, Weiid, NEs, Net, NEmin, APs, Apt, APmin, MIAPfStL, MINECo, MINETfstL, MIAPRec, MIWReu	Quantitative	M1	Environmental performance
ILC, IIWD	Dependent	M2	
NEPV, APPV,	Qualitative	M3	
WVWA, WILC, WVEIID		M4	
EPIMW, WMaxJO, EMinJO, Wpimw, Wjo, Wpwe, Wos, Wlh,	Quantitative	M1	Social performance

Wridsi, Wpariwd, OSt, Oss			
APIMW, PViidsi, CPWE, PWE, OS, CSO	Dependent	M2	
VJO, WVpimw, WPVpwe, WVlh,	Qualitative	M6	
AJO		M7	
WPVos		M5	
WPVpariwd		M4	
Wecpv Wenpv Wsopv	Quantitative	M1	Effectiveness of C&D waste management

6.5 Model Validation

After all the variables are quantified and their functions determined, tests should be conducted to build up confidence in the model (Sterman, 2000), and to ensure the accuracy of the model for reflecting the real world in a meaningful way (Richardson and Pugh, 1989). As stated by Forrester and Senge (1980), no single test can serve to validate a SD model; instead, confidence in a SD model accumulates gradually as the model passes more tests and as new points of correspondence between the model and empirical reality are identified. Coyle (1983) proposed the main tests that should be carried out to validate a SD model, including:

1. Verification tests, which are concerned with verifying that the structure and parameters of the real system have been correctly transcribed into the model;
2. Validation tests, which are concerned with demonstrating that the model

actually generates the same type of behavior that would be expected from the real system;

3. Legitimation tests, which are applied to determine that the model follows the laws of system structure or any generally accepted rules.

These testing methodologies are used in this study. The purpose of applying these rigorous tests is to ensure that there is nothing in the dynamic model that is not in the real world and nothing significant in the real world that is not incorporated in the model. Coyle (1996) further suggested a number of steps and guidelines which could apply to dynamic models to help build confidence in them, typically including:

- The causal loop diagram must correspond to the statement of the problem.
- The equations must correspond to the causal loop diagram; in particular, the '+' and '-' signs in the equations must match the signs in the causal loop diagram.
- The model must be dimensionally valid, i.e. the dimensions (or unit of measurement) of the variables on the right-hand side of the equation should be able to be converted to the dimension of the variable on the left-hand side of the equation.
- The behavior of the model must be plausible – what it does should be what we expect it to do.
- Determination of whether the model behaves properly when subjected to

extreme conditions.

The dynamic model for assessing the effectiveness of C&D waste management developed previously is adopted herein to illustrate the validation process based on the above guidelines. The purpose of the tests is to give decision-makers confidence in the model so that it can be used to assess the effectiveness of C&D waste management, and further, as a platform for experimenting with different managerial policies. The following tests are conducted for validation:

TEST 1: The causal loop diagram for assessing the effectiveness of C&D waste management must correspond to the statement of the problem.

The causal loop diagrams described in Chapter 5 (from Figure 5.4 to Figure 5.35) comprises four subsystems, encompassing 'C&D waste generation', 'economic performance', 'environmental performance' and 'social performance'. These subsystems as a whole correspond to the statement of the research problem, which is to assess the effectiveness of C&D waste management with a main focus on the economic, environmental and social impacts of waste management activities. It is therefore considered these diagrams are effective.

TEST 2: The equations must correspond to the causal loop diagram; in particular, the '+' and '-' signs in the equations must match the signs in the causal loop diagram.

A closer examination of the equations in the dynamic model indicates that all directions of relationships showing in the model equations match well with the corresponding directions in the causal loop diagrams described in Chapter 5. A detailed list of model equations is attached as Appendix B.

TEST 3: The model must be dimensionally valid, i.e. the dimensions (or unit of measurement) of the variables on the right-hand side of the equation should be able to be converted to the dimension of the variable on the left-hand side of the equation.

This test can be used to check and ensure the consistency of variable dimensions of each model equation. Taking the variable 'WGaRM' in the subsystem of C&D waste generation (in Figure 5.36) as an example, related equations include:

WGaRM(t) = WGaRM(t - dt) + (WGR - RW) * dt

INIT WGaRM = 0

INFLOWS:

WGR = CFAM*WGFA

OUTFLOWS:

RW = WGaRM*WRR

Where WGaRW – Total C&D waste generation after adopting waste reduction measures;

WGR – C&D waste generating rate;

RW – Reducing C&D waste;

CFAM – Constructed floor area monthly;

WGFA – Average C&D waste generation per floor area;

WRR – C&D waste reduction rate.

Variable dimensions of the equation are illustrated by using the following chart:

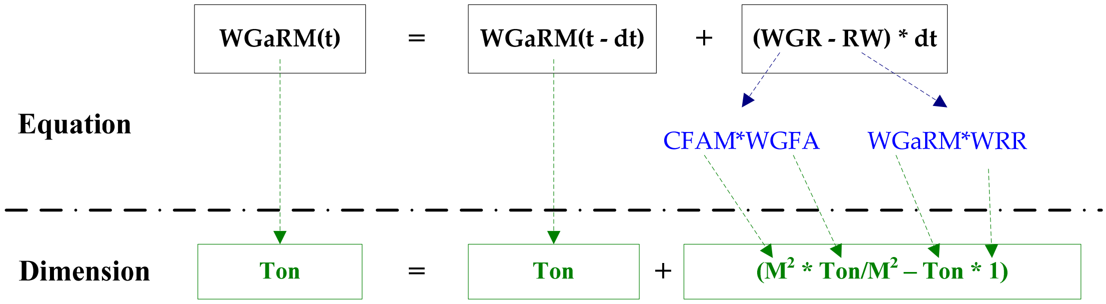

Figure 6.3: An example of variable dimensions check

It is apparent that the variable dimension on the left-hand side is consistent with the variable dimension on the right-hand side of the equation. All equations in the model have been checked in the similar way to ensure dimension consistency.

TEST 4 The behavior of the model must be plausible – what it does should be what we expect it to do.

This validation is performed through sensitivity analysis. Sensitivity analysis is the procedure by which tests for understanding how the proposed model will behave if the variable values are varied over a reasonable range are carried out (Maani and Cavana, 2000). It is therefore regarded as an important part to ensure the robustness of the model. An example shown in Figure 6.4 demonstrates how the variable 'WMCwo' (C&D waste management culture within an organization) varies in line with the alteration in variable 'ULC' (unit landfilling charge). Two main conclusions can be drawn from results of the sensitivity analysis. One is that C&D waste management culture within an organization could be gradually promoted through implementing a waste landfilling charge. This is in accordance with the findings by Kibert et al. (2000) and Hao et al. (2008a), who stated that waste landfilling charge is an effective instrument for forcing contractors and developers to reduce waste. The other is that all curves under five different scenarios exhibit a similar shape, demonstrating the fact that the larger a waste landfilling charge, the better the waste management culture within an organization. This echoes the findings by Hao et al. (2008a) reporting that management of C&D waste in Hong Kong has been improved after imposing a higher waste charging scheme since 2005. Therefore, it can be concluded that the model can correctly predict the outcome of changes in variables.

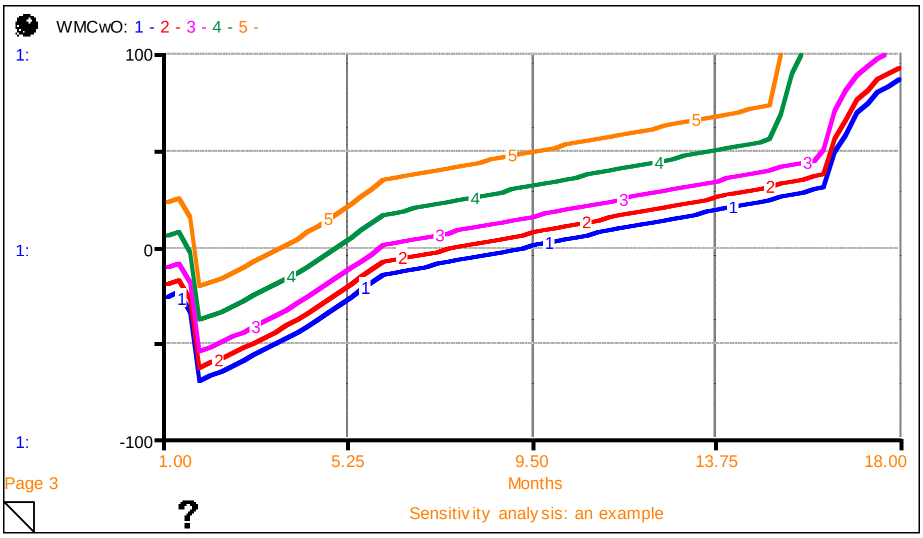

Figure 6.4: An illustration of model validation

(1 for unit landfill charge = 6; 2 for unit landfill charge = 34.5; 3 for unit landfill charge = 63; 4 for unit landfill charge = 91.5; 5 for unit landfill charge =120.)

Test 5: Determine whether the model behaves properly when subjected to extreme conditions.

According to the proposed model in Figure 5.36, the variable FDCs (Frequency of design changes) can be affected by variable EMfWRD (Effects of measures taken for C&D waste reduction in project design). They are all qualitative variables and thus quantified based on a scale ranging from 0 to 100, with 0 having the lowest frequency of design change and lowest effect of measures on C&D waste reduction in project design, respectively, and 100 having the highest frequency of design changes and best effect of measures on waste reduction in project design, respectively. Furthermore, a value of 15 is assigned to EMfWRD in the base scenario. Results of the three scenarios (the base scenario and two extreme condition scenarios) are shown in Figure 6.5.

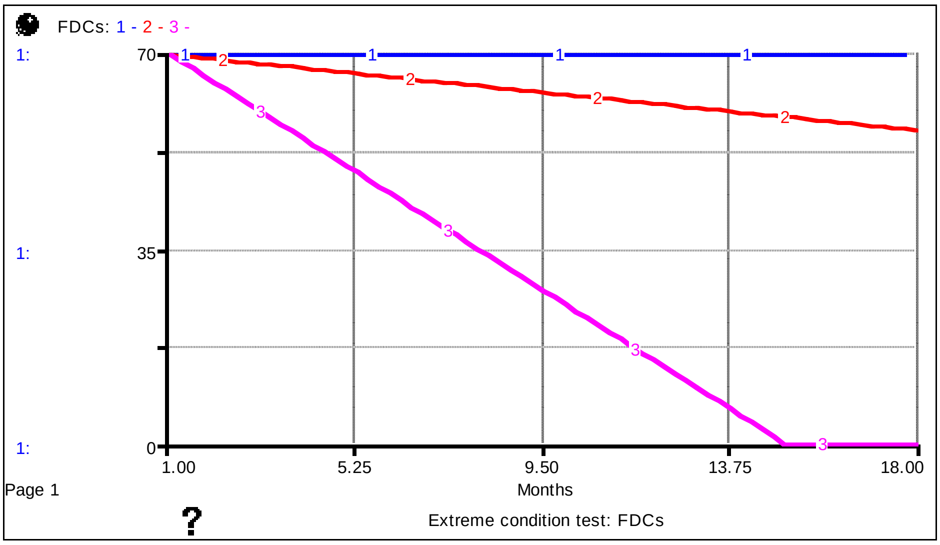

Figure 6.5: An example of extreme conditions test

(Curve 1: EMfWRD = 0; Curve 2: EMfWRD = 15; Curve 3: EMfWRD = 100)

Value of FDCs will remain when no measures (extreme condition one) are adopted to reduce design changes. When the measures corresponding to the level of 15 are taken for reducing design changes, the occurrence frequency of design changes decreases gradually and it will be reduced from 70 (in the extreme condition one) to 56 at the end of the simulation period. In another extreme condition scenario, a hypothesized situation where greatest efforts are devoted to minimizing design changes, simulation results indicate that the frequency of design changes decrease dramatically and from the 15th month onward, no design changes will happen. These results from the extreme condition tests are in accordance with the general understanding of how managing design changes would affect the occurrence frequency of design changes. In this way, extreme condition tests on other variables in the model are conducted and analyzed.

Results of the above tests have confirmed that the proposed model can reasonably reflect the C&D waste management situation in the real world. It is therefore robust to be used for simulation.

6.6 Results of the case study

Based on the methods for variable quantification introduced in Section 6.4, all variables required as inputs into the model can be quantified accordingly. Table 6.3 and Table 6.4 tabulate the data fed into the C&D waste management effectiveness assessment model; the value rangeability for each inputting variable is presented as well.

Table 6.3: Major data fed into the dynamic model

Variables	Values	Value rangeability	Subsystem
CFAM	(46999.5/18)m^2	>0	C&D waste generation
EIRPWtRW	60	[0, 100]	
ELALWT	40	[0, 100]	
EMfWRD	15	[0, 100]	
SSL	See Table 6.4		
WGFA	(47.6/1000)ton/m^2	>0	
A&CRF	30	[0, 100]	Economic performance
AUPNW	360yuan/ton	>0	
NPWMs	0	n/a	
NPWMmax	50000yuan	n/a	
NPWMt	-10000yuan	n/a	
UCPM	60yuan/ton	>0	
UCTfStL	2.5yuan/ton/km	>0	
UCWCo	15yuan/ton	>0	
UCWRec	20yuan/ton	>0	
UCWReu	15yuan/ton	>0	
UCWS	15yuan/ton	>0	
ULC	5.88yuan/ton	>0	
UPID	60yuan/ton	>0	
TDfStL	16km	>0	
APmin	15	[0, 100]	Environmental performance
APs	65	[0, 100]	
Apt	80	[0, 100]	
MIAPRec	0.5	(0, 1)	

MIDW	0.02	(0, 1)	
MINECo	0.5	(0, 1)	
MINETfStL	0.5	(0, 1)	
MIWReu	0.5	(0, 1)	
MIWDL	0.0667m^2/ton	>0	
NEmin	30	[0, 100]	
NEs	65	[0, 100]	
Net	80	[0, 100]	
Wap	1/5	[0, 1]	
Weiid	1/5	[0, 1]	
Wiwp	1/5	[0, 1]	
Wlao	1/5	[0, 1]	
Wne	1/5	[0, 1]	
AJO	See Table 6.4		Social performance
EMaxJO	20	>0	
EMinJO	4	>0	
EPIMW	60	>0	
LH	100 (initial value)	[0, 100]	
Oss	60	[0, 100]	
OSt	30	[0, 100]	
Wjo, Wlh, Wos, Wpariwd, Wpimw, Wridsi, Wps, Wpwe	1/8	[0, 1]	
W	1	Constant	Effectiveness of C&D waste management
Wecpv	1/3	[0, 1]	
Wenpv	1/3	[0, 1]	
Wsopv	1/3	[0, 1]	

Table 6.4: Values of SSL and AJO

Month	Value of SSL	Value of AJO
1	0	0
2	5	2
3	10	2
4	25	5
5	30	5
6	30	8
7	30	8
8	30	13
9	40	13
10	40	15
11	40	15
12	40	15
13	40	23
14	40	23
15	40	23
16	35	23
17	30	16
18	20	16
Value rangeability	[0, 100]	>0

After importing all data into the model and defining the interrelationships of all independent variables, the model can be used for simulation with the aid of iThink software. In the case study, the model is simulated in a total period of 18 months, which is corresponding to the construction duration of the project as indicated in Chapter 5. Results of model simulation are exhibited and discussed in the following sections.

6.6.1 Results of the subsystem of C&D waste generation

Figure 6.6, Figure 6.7, Table 6.5 and Figure 6.8 exhibit the simulation outcomes of the subsystem of C&D waste generation. Figure 6.6 shows simulation results of four outputs, namely, IDCs, IWMCwO, CIWR, and IALWT. Figure 6.7 exhibits simulation results of IMCWR, IIWM, ISSL and EtRW. Table 6.5 tabulates in detail the simulation outcomes of seven variables over the project duration, including IDCs, IWMCwO, CIWR, IALWT, IMCWR, IIWM and ISSL. Figure 6.8 shows simulation results of four variables in related to C&D waste generation and reduction, including WGR, RW, WGM and AAWR.

In Figure 6.6, IDCs is a variable for measuring the impacts of occurrence frequency of design changes on C&D waste reduction. IWMCwO is used to study how C&D waste management culture within an organization which varies over the project duration will affect C&D waste reduction. CIWR investigates the cost impact on C&D waste reduction, including costs of C&D waste collection, sorting and disposal. Furthermore, IALWT is used to show how application of low-waste construction technologies, such as prefabrication, will reduce the generation of C&D waste. Each of the four variables can range from -100 to 100, with -100 standing for the highest negative impact on C&D waste reduction and 100 standing for the highest positive impact.

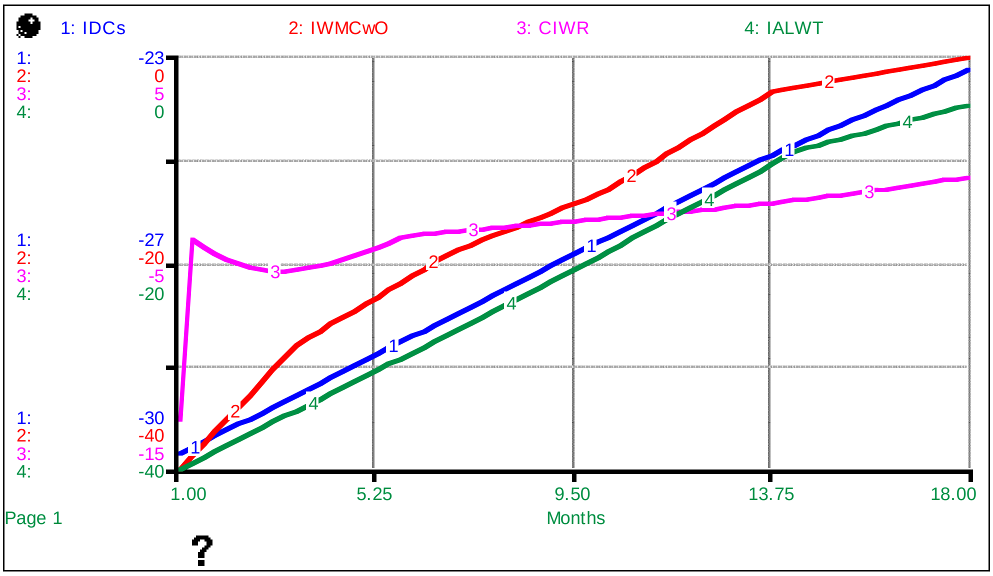

Figure 6.6: Simulation results of the C&D waste generation subsystem

As demonstrated by Curve 1, 2 and 4 in Figure 6.6, values of IDCs, IWMCwO and IALWT approximately increase in linear, indicating that adverse effects on C&D waste reduction from occurrence frequency of design changes, cost concern and application of low-waste construction technologies all decrease significantly along with the construction project proceeds. For example, although IWMCwO (impacts of C&D waste management culture within an organization) is valued -40 at the beginning (Curve 2), it is projected to receive a higher value of 0 in the 18th month. Curve 3 shows that value of CIWR is relatively low at the beginning (value: -12.65), and then it increases sharply in the second month to -4.83. In the following two months, CIWR decreases slightly, and after that it increases steadily, reaching a value of -0.80 at the end of the project. Variation of CIWR implies that adverse influence of cost concern on C&D waste reduction is obvious in the first four months; after that, the adverse impact is gradually reduced.

Figure 6.7 exhibits simulation results of IMCWR, IIWM, ISSL and EtRW. IMCWR is a variable to show the influence of managers' management capacity on promoting C&D waste minimization. IIWM is to investigate how the investment in C&D waste management could contribute to waste minimization. ISSL is used to study how the constraint of construction site space will affect C&D waste reduction over the project duration. All the three variable range from -100 to 100, with -100 indicating the highest negative impact on C&D waste reduction and 100 indicating the highest positive impact. EtRW is a variable to measure the efforts devoted to C&D waste reduction in the project under study. According to the model, EtRW is the synthesized effect of the above seven variables, i.e., IDCs, IWMCwO, CIWR, IALWT, IMCWR, IIWM and ISSL. Value of EtRW can range from -100 to 100, with -100 demonstrating the lowest effort and 100 demonstrating the highest effort.

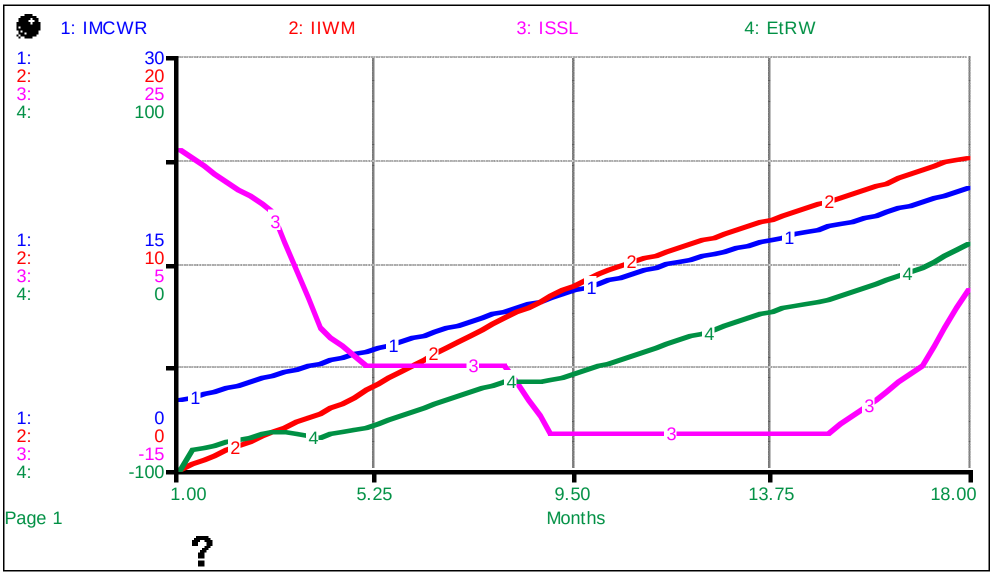

Figure 6.7: Simulation results of the subsystem of C&D waste generation

As shown in Figure 6.7, values of both IMCWR and IIWM increase dramatically from 5 (1st month) to 20.5 (18th month) and from 0 (1st month) to 15.13 (18th month), respectively. This means that improvements on management capacity and investment in C&D waste management contribute significantly to the minimization of C&D waste. With respect to ISSL, the variation of its value over the investigated period is to some extent similar to a U shape, higher in the first three and last three months, but lower in the middle of the period. The influence of the constraint of construction site space on C&D waste reduction reaches to the bottom (value: -11.5) during the 9th and 15th months.

As mentioned above, seven variables in the model, including IDCs, IWMCwO, CIWR, IALWT, IMCWR, IIWM and ISSL, are the major determinants of the effect of C&D waste reduction. Table 6.5 tabulates in detail the simulation outcomes of these variables over the project duration. It is apparent that IDCs, IWMCwO, CIWR and IALWT receive higher negative values, indicating that ‘occurrence frequency of design changes’, ‘waste management culture within an organization’, ‘cost concern about C&D waste reduction’ and ‘adoption of low-waste construction technologies’ contribute most to the generation of C&D waste in the studied case. IMCWR is the only variable having positive values throughout the whole project duration, demonstrating that C&D waste management capacity leads positive effects to the reduction of C&D waste. Based on these results, it can be roughly confirmed that in the project under study, according to the positive contribution to C&D waste reduction, variables in descending order can be arranged as:

IMCWR>IIWM>ISSL>CIWR>IWMwO>IALWT>IDCs.

Table 6.5: Detailed simulation results of variables affecting waste reduction

Months	IDCs	IWMCwO	CIWR	IALWT	IMCWR	IIWM	ISSL
1.00	-29.75	-40.00	-12.65	-40.00	5.00	0.00	16.00
2.00	-29.35	-35.20	-4.83	-37.75	5.90	0.90	13.00
3.00	-28.95	-30.40	-5.41	-35.50	6.80	1.80	10.00
4.00	-28.55	-26.65	-5.14	-33.25	7.70	2.70	-1.25
5.00	-28.15	-23.95	-4.45	-31.00	8.60	3.80	-5.00
6.00	-27.75	-21.25	-3.63	-28.75	9.50	5.00	-5.00
7.00	-27.35	-18.70	-3.45	-26.50	10.50	6.20	-5.00
8.00	-26.95	-16.90	-3.26	-24.20	11.50	7.35	-5.00
9.00	-26.55	-15.10	-3.07	-21.80	12.50	8.40	-11.50
10.00	-26.15	-13.30	-2.88	-19.40	13.50	9.45	-11.50
11.00	-25.75	-10.75	-2.68	-17.00	14.50	10.24	-11.50
12.00	-25.35	-8.05	-2.47	-14.60	15.30	10.94	-11.50
13.00	-24.95	-5.35	-2.24	-12.20	16.10	11.64	-11.50
14.00	-24.58	-3.20	-2.00	-9.80	16.90	12.34	-11.50
15.00	-24.24	-2.40	-1.74	-8.20	17.70	13.04	-11.50
16.00	-23.90	-1.60	-1.45	-7.00	18.50	13.74	-8.25
17.00	-23.56	-0.80	-1.14	-5.80	19.50	14.56	-5.00
Final	-23.22	0.00	-0.80	-4.60	20.50	15.13	2.50

Figure 6.8 shows simulation results of four variables in related to C&D waste generation and reduction, including WGR, RW, WGM and AAWR. WGR means the amount of C&D waste generated per month. In fact, it is an input and is set as constant with a value of 124.29ton (evidenced by Curve 1 in the Figure). RW is a variable to simulate the amount of reduced C&D waste per month. Curve 2 exhibits that the amount of C&D waste reduction, which increases month by month, except for a decline in the 4th month. WGM examines monthly C&D waste generation in the project. From a mathematical point of view, WGR is calculated through the equation of 'WGR = RW + WGM'. Considering RW remains unchanged over the project duration, pattern of Curve 3, which is the

simulation result of WGM, shows a shape that is symmetrical with Curve 2. These two curves demonstrate that the effect of C&D waste reduction increases with the project proceeds. Additionally, the variable AAWR is used to investigate the cumulative amount of C&D waste reduction at any time point within the project duration. Apparently, it indicates an exponential growth, and the total volume of reduced C&D waste amounts to 283.93ton, achieving a rate of 12.7% in C&D waste reduction.

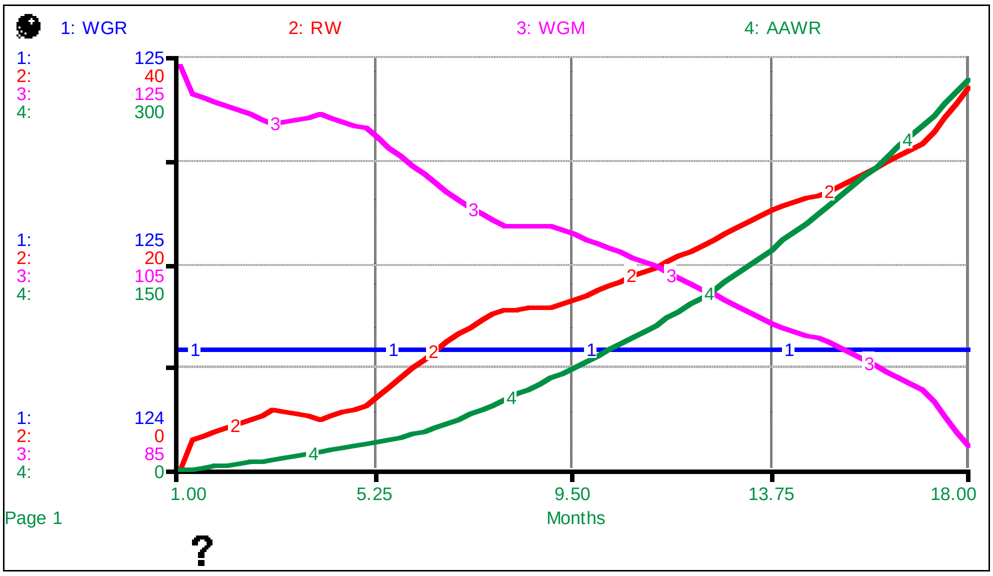

Figure 6.8: Simulation results of C&D waste generation and reduction

6.6.2 Results of the subsystem of economic performance

Simulation results of the subsystem of economic performance are exhibited in Table 6.6, Table 6.7 and Figure 6.9. Table 6.6 lists the results in relation to C&D waste generation and disposal in the project under study, including CoW (amount of collected waste per month), SW (amount of sorted waste per month), ReuW (amount of reused waste per month), RecW (amount of recycled waste per month), IDW (amount of waste illegally dumped per month) and WDLM (amount of waste disposed of at landfills per month). Table 6.7 tabulates the cost regarding C&D waste management, including CWCo (cost of C&D waste collection), CWS (cost of C&D waste sorting), CWReu (cost of waste reuse), CWRec (cost of waste recycling), CWTfStL (cost of C&D waste transportation from construction site to landfills), CWDL (cost of C&D waste disposal at landfills), and CHIDW (cost of handling illegally dumped C&D waste). Figure 6.9 shows the simulation results of cost and economic benefit of C&D waste management in the project.

It can be seen from Table 6.6 that during the project duration, the amount of waste collection is relatively steady which approximates to an average value of 58ton. Values of SW, ReuW and RecW increase gradually. Furthermore, value of IDW increases in the first 9 months, from 7.34ton to 25.83ton, and then decreases gradually to 20.19ton in the 18th month. WDLM presents a similar variation, increasing in the first 4 months and deceasing gradually over the period remaining. Values of five variables, i.e. SW, ReuW, RecW, IDW and WDLW, have demonstrated clearly that management of C&D waste in the studied project is improved gradually when the project proceeds. It also needs to be pointed out that according to values of IDW and WDLW, the majority of generated C&D waste in the project is disposed of, either at landfills or illegal dumps.

Table 6.6: Results of amount of C&D waste

Months	CoW	SW	ReuW	RecW	IDW	WDLM
1.00	57.02	10.76	0.52	0.24	7.34	66.50
2.00	56.87	26.15	3.89	1.77	18.44	68.78
3.00	57.33	30.68	6.73	3.06	22.38	74.24
4.00	58.34	32.16	8.15	3.71	24.18	77.76
5.00	58.61	32.67	8.79	4.00	25.18	77.64
6.00	58.23	32.66	9.04	4.11	25.59	75.21
7.00	57.96	32.47	9.10	4.14	25.66	72.46
8.00	58.52	32.44	9.08	4.13	25.66	69.94
9.00	59.43	32.91	9.12	4.15	25.83	68.58
10.00	59.69	33.47	9.23	4.20	25.83	66.78
11.00	59.78	34.03	9.38	4.27	25.58	65.05
12.00	59.55	34.57	9.53	4.33	25.10	63.47
13.00	59.24	35.09	9.68	4.40	24.40	61.84
14.00	59.23	35.72	9.83	4.47	23.56	60.28
15.00	59.26	36.63	10.02	4.56	22.66	59.01
16.00	58.77	37.58	10.27	4.67	21.56	57.56
17.00	57.37	38.37	10.52	4.78	20.19	56.44
Final						54.21

Table 6.7 tabulates the cost regarding C&D waste management, including CWCo (cost of C&D waste collection), CWS (cost of C&D waste sorting), CWReu (cost of waste reuse), CWRec (cost of waste recycling), CWTfStL (cost of C&D waste transportation from construction site to landfills), CWDL (cost of C&D waste disposal at landfills), and CHIDW (cost of handling illegally dumped C&D waste). The results of these variables reflect the costs corresponding to the waste streams involved in Table 6.6. For example, CWCo is related to CoW, which is used to examine the accumulative amount of cost for C&D waste collection, while CWTfStL, CWDL are concerning WDLM, which are to simulate the

transportation and disposal cost for C&D waste disposal. It can be seen clearly that various streams of costs for C&D waste management in the project can be arranged according to their orders of magnitude as: CHIDW>CWCo>CWTfStL>CWS>CWDL>CWReu>CWRec. This indicates that the majority of C&D waste management cost in the project is used for dealing with C&D waste disposal (CHIDW, CWTfStL and CWDL) and waste collection (CWCo).

Table 6.7: Results of various costs of C&D waste management

Table 3 ()

Months	CWCo	CWS	CWReu	CWRec	CWTfStL	CWDL	CHIDW
1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	855.31	161.39	7.87	4.77	44.43	388.13	440.69
3.00	1,708.32	553.68	66.23	40.16	373.81	806.09	1,547.13
4.00	2,568.21	1,013.81	167.14	101.36	943.36	1,251.55	2,890.03
5.00	3,443.27	1,496.15	289.45	175.53	1,633.76	1,709.55	4,340.89
6.00	4,322.43	1,986.24	421.32	255.50	2,378.07	2,160.98	5,851.41
7.00	5,195.83	2,476.13	556.93	337.74	3,143.48	2,597.20	7,386.59
8.00	6,065.22	2,963.20	693.36	420.47	3,913.51	3,017.37	8,926.34
9.00	6,942.98	3,449.85	829.62	503.10	4,682.59	3,425.55	10,466.08
10.00	7,834.43	3,943.42	966.40	586.05	5,454.62	3,824.73	12,015.91
11.00	8,729.83	4,445.46	1,104.91	670.05	6,236.41	4,213.57	13,565.77
12.00	9,626.59	4,955.94	1,245.57	755.35	7,030.35	4,592.69	15,100.81
13.00	10,519.86	5,474.51	1,388.52	842.04	7,837.18	4,962.26	16,606.63
14.00	11,408.49	6,000.93	1,533.69	930.07	8,656.59	5,322.33	18,070.42
15.00	12,296.88	6,536.77	1,681.16	1,019.51	9,488.97	5,673.82	19,484.12
16.00	13,185.82	7,086.16	1,831.53	1,110.69	10,337.70	6,017.55	20,843.96
17.00	14,067.31	7,649.85	1,985.55	1,204.10	11,207.04	6,353.56	22,137.43
Final	14,927.94	8,225.46	2,143.32	1,299.77	12,097.53	6,680.84	23,348.59

Figure 6.9 shows the simulation results of cost and economic benefit of C&D waste management in the project.

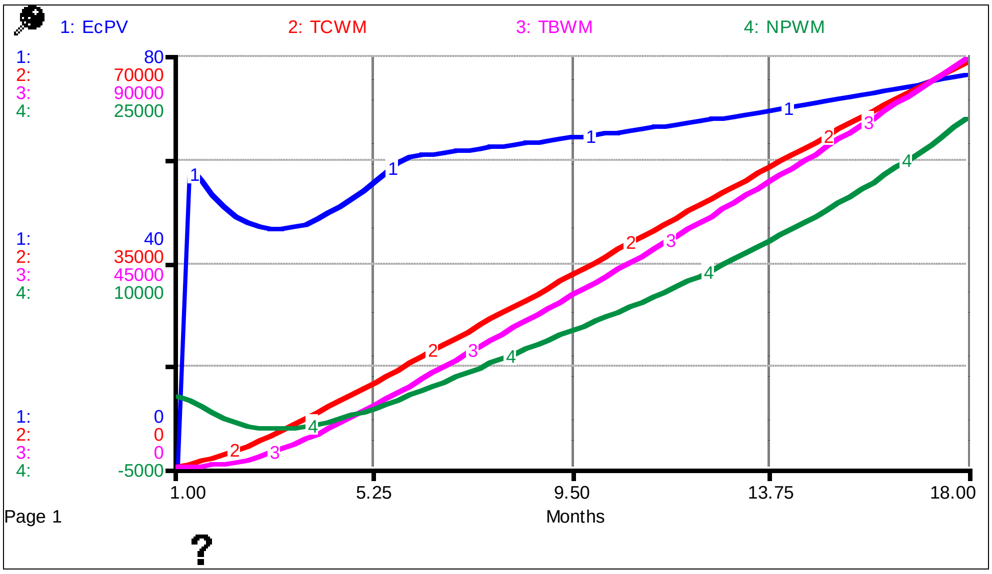

Figure 6.9: Results of cost and benefit of C&D waste management

In the Figure, TCWM and TBWM represent the total cost and total economic benefit of implementing C&D waste management, respectively. NPWM is the net profit of the implementation of waste management, which equals to TBWM minus TCWM. EcPV is a variable for investigating the economic effectiveness of C&D waste management; particularly, it is calculated as follows:

EcPV = IF TIME=1 THEN 0 ELSE

IF NPWM>=NPWMmax THEN 100 ELSE

IF NPWM>=NPWMs and NPWM<NPWMmax THEN

((NPWM-NPWMs)/NPWMmax-NPWMs)*40+60 ELSE

IF NPWM>=NPWMt and NPWM<NPWMs THEN

60*(NPWM-NPWMt)/(NPWMs-NPWMt) ELSE -100

Where: EcPV – Economic performance value of C&D waste management;

NPWM –The net profit by conducting C&D waste management in the project;

NPWMmax – The maximum net profit by conducting C&D waste management in the project;

NPWMs – The standard value of net profit by conducting waste management in the project;

NPWMt – Intolerable net profit by conducting C&D waste management in the project

It can be seen from the results that both TCWM and TBWM increase linearly, reaching a total amount of 68,723.46Yuan and 89,050.31Yuan at the end of the project, respectively. Value of NPWM is negative during the first 5-month period; afterwards it increases dramatically, amounting to 20326.85Yuan in the 18th month. This implies that the implementation of C&D waste management in the studied project is economically feasible in the first 5 months, but it is economically beneficial from the 6th month onward. Furthermore, the curve of EcPV demonstrates that economic performance of C&D waste management of the project is improving from the 3rd month onward, and EcPV receives a value of 76.26 finally.

6.6.3 Results of the subsystem of environmental performance

Simulation results of the subsystem of environmental performance are exhibited in Table 6.8 and Figure 6.10. Table 6.8 tabulates values of variables examining the impacts that C&D waste management activities would have on the environment, which include WILC (weighted impacts of land consumption due to C&D waste landfilling), WVWQ (weighted value of water quality), WVNE (weighted value of noise emission), WVAP (weighted value of air pollution), and WVEIID (weighted value of environmental impacts of illegally dumped C&D waste on public living environment). Figure 6.10 shows the value of EnPV throughout the project duration.

Table 6.8: Results of the subsystem of environmental performance

Table 5 ()

Months	WILC	WVWQ	WVNE	WVAP	WVEIID	EnPV
1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	-0.02	0.00	-0.24	-1.42	-0.03	-1.71
3.00	-0.09	-0.20	-1.07	-3.44	-0.10	-4.91
4.00	-0.18	-0.40	-1.67	-4.33	-0.19	-6.77
5.00	-0.28	-0.60	-1.95	-4.77	-0.29	-7.89
6.00	-0.39	-1.10	-1.99	-4.97	-0.39	-8.84
7.00	-0.50	-1.60	-1.97	-5.02	-0.49	-9.59
8.00	-0.62	-2.10	-1.97	-5.02	-0.60	-10.31
9.00	-0.73	-2.60	-2.12	-5.04	-0.70	-11.19
10.00	-0.84	-3.10	-2.18	-5.08	-0.80	-12.00
11.00	-0.96	-3.60	-2.23	-5.10	-0.90	-12.79
12.00	-1.07	-4.10	-2.25	-5.08	-1.01	-13.51
13.00	-1.18	-4.60	-2.25	-5.02	-1.11	-14.16
14.00	-1.29	-5.10	-2.27	-4.93	-1.20	-14.80
15.00	-1.41	-5.60	-2.34	-4.84	-1.30	-15.48
16.00	-1.52	-6.10	-2.35	-4.75	-1.39	-16.10
17.00	-1.62	-6.60	-2.33	-4.62	-1.48	-16.65
Final	-1.73	-7.10	-2.07	-4.39	-1.56	-16.85

Table 6.8 tabulates values of variables examining the impacts that C&D waste management activities would have on the environment, which include WILC, WVWQ, WVNE, WVAP, and WVEIID. In view that each of the five variables is hypothesized to have an equal weight of 0.2 in the model, each of them can range

from -20 to 20 (100*0.2=20), with -20 indicating the highest adverse environmental impact and 20 indicating the highest positive environmental impact. Additionally, Table 6.8 also shows values of EnPV (environmental performance value) over the whole period of 18 months. EnPV is a variable for measuring the environmental performance of C&D waste management activities in the investigated project. It ranges from -100 to 100, with -100 representing the lowest environmental performance and 100 representing the highest environmental performance. Variation of EnPV throughout the project duration is also illustrated in Figure 6.10.

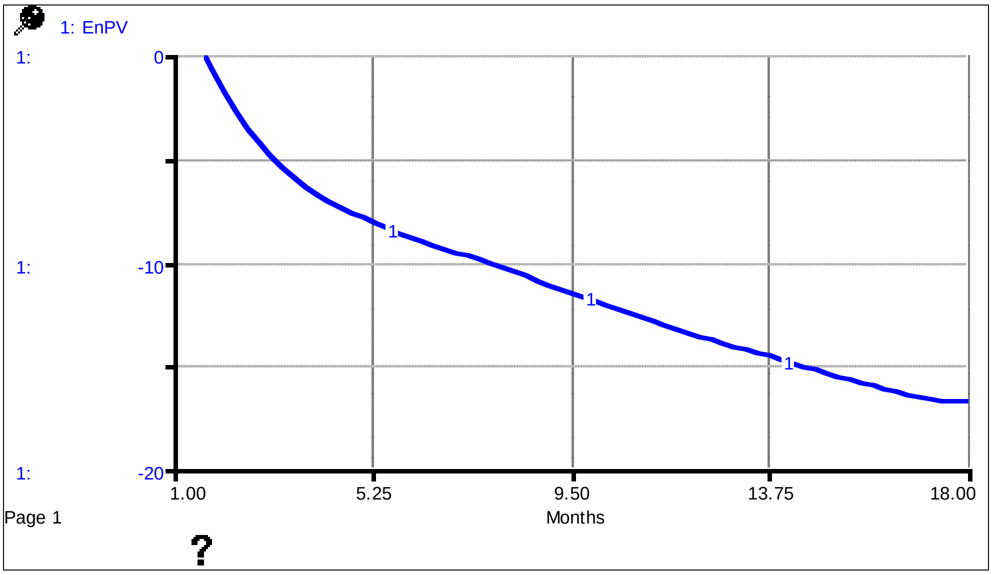

Figure 6.10: Results of environmental performance value

It can be observed from the simulation results that throughout the whole C&D waste management process, air pollution (WVAP) contributes the most to adverse impacts on the environment, followed by water pollution from C&D waste management (WVWQ). The least contributor is the environmental impacts from illegally dumped C&D waste on the public living environment (WVEIID). However, it should be pointed out that weighted values of all variables are negative (see Table 6.8), which echoes with findings from previous studies by Shen et al. (2004) and Tam and Tam (2008), who stating that C&D waste management is by nature not environmentally friendly. This also leads to values of EnPV presenting a similarly exponential decline, from -1.71 at the beginning of the project to -16.85 at the end. This indicates that the environmental performance of C&D waste management of the studied construction project becomes worse and worse along with the project proceeds.

6.6.4 Results of the subsystem of social performance

Simulation results of the subsystem of social performance are shown in Table 6.9 and Figure 6.11. Table 6.9 lists weighted values of eight variables in terms of the social influence of C&D waste management activities, which encompass WVpimw (weighted value of practitioners' initiative to minimize C&D waste), WVjo (weighted value of provision of job opportunities), WPVpwe (weighted performance value of physical working environment in C&D waste management), WPVos (weighted performance value of operatives' safety in C&D waste management), WPVlh (weighted value of practitioners' long-term health), WPVridsi (weighted performance value of regulating illegal C&D waste disposal to improve city image), WPVps (weighted value of public satisfaction about waste management performance) and WPVpariwd (weighted performance value of public appeal for regulating illegal C&D waste dumping). Figure 6.11 exhibits the results of SoPV.

Table 6.9 lists weighted values of eight variables in terms of the social influence of C&D waste management activities, encompassing WVpimw, WVjo, WPVpwe, WPVos, WPVlh, WPVridsi, WPVps and WPVpariwd. Since the total weight of the eight variables is 1 and each of them is assigned equally in this case, each of them obtains a weight of 1/8. Therefore, all the variables can range from -12.5 to 12.5 (100*1/8=12.5), with -12.5 having the highest negative social impact and 12.5 having the highest positive social impact.

Table 6.9: Results of the subsystem of social performance

Table 8 ()

Months	WVpimw	WVjo	WPVpwe	WPVos	WVlh	WPVridsi	WPVps	WPVpariw	SoPV
1.00	0.00	-12.50	-2.50	0.00	0.00	0.06	1.50	3.75	-9.69
2.00	0.25	-12.50	-2.75	-0.25	-0.13	0.46	1.17	3.75	-10.00
3.00	0.50	-12.50	-3.00	-0.50	-0.25	0.83	0.85	3.75	-10.32
4.00	0.75	0.78	-3.25	-0.75	-0.38	1.31	3.21	3.75	5.42
5.00	1.00	0.78	-3.50	-1.00	-0.69	1.77	2.91	3.75	5.03
6.00	1.25	3.13	-3.75	-1.25	-1.00	2.23	3.09	3.75	7.44
7.00	1.50	3.13	-4.00	-1.50	-1.31	2.68	2.79	3.75	7.03
8.00	1.75	7.03	-4.25	-1.75	-1.63	3.10	3.28	3.75	11.29
9.00	2.00	7.03	-4.50	-2.00	-1.94	3.48	2.99	3.75	10.81
10.00	2.25	8.59	-4.75	-2.25	-2.25	3.80	3.01	3.75	12.16
11.00	2.50	8.59	-5.00	-2.50	-2.56	4.11	2.72	3.75	11.61
12.00	2.75	8.59	-5.25	-2.75	-2.88	4.39	2.43	3.75	11.04
13.00	3.00	12.50	-5.50	-3.00	-3.09	4.65	2.92	3.75	15.23
14.00	3.25	12.50	-5.75	-3.25	-3.28	4.90	2.64	3.75	14.75
15.00	3.50	12.50	-6.00	-3.50	-3.47	5.13	2.35	3.75	14.26
16.00	3.75	12.50	-6.25	-3.75	-3.66	5.35	2.06	3.75	13.75
17.00	4.00	9.38	-6.50	-4.00	-3.84	5.55	1.14	3.75	9.47
Final	4.25	9.38	-6.75	-4.25	-4.03	5.74	0.85	3.75	8.93

The results from the simulation show that four variables, including WVpimw, WPVridsi, WPVps and WPVpariwd, receive positive values throughout the simulation period, indicating that in the project under study, all the variables affecting the social performance make positive contributions to society, which are ‘practitioners’ initiative to minimize waste’, ‘regulating illegal waste dumping’, ‘public satisfaction about waste management’ and ‘public appeal for regulating illegal waste disposal’. Three variables, including WPVpwe, WVos and WPVlh, obtain negative values, demonstrating that ‘physical working environment in waste management’, ‘operatives’ safety’ and ‘practitioners’ long-term health’ need to be improved to reduce the adverse influence of C&D waste management activities on the society. Additionally, WVjo shows that from the 4th to 18th month, C&D waste management in the project can contribute to the society by providing new job opportunities.

Furthermore, the results in Figure 6.11 also show clearly how SoPV varies over the project duration. SoPV is a variable for examining the social impact of C&D waste management of the project investigated. It can range from -100 to 100, with -100 indicating the highest negative impact that C&D waste management activities would impose on the society and 100 indicating the highest positive influence. The curve in Figure 6.11 shows that SoPV of the project is projected to present a ladder-type growth in the first 15 months, reaching a value of 14.26 at the end of the 15th month. Although it decreases gradually to 8.93 at the end of the project, it is worth highlighting that the social performance associated with C&D waste management in the project has been improving.

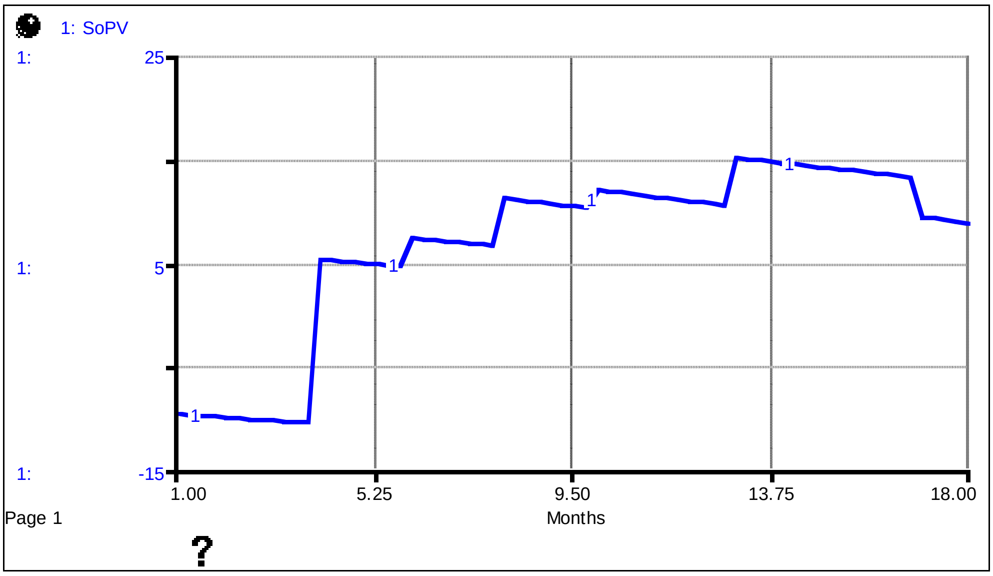

Figure 6.11: Results of social performance value

6.6.5 The overall results of the effectiveness of C&D waste management

Figure 6.12 illustrates values of WcPV, EnPV, SoPV and **Ewm**. Simulation results of WcPV, EnPV and SoPV have been discussed in the previous sections. **Ewm** is used to investigate the overall effectiveness of C&D waste management activities of the project, which can range from -100 to 100, with -100 having the lowest effectiveness and 100 having the highest effectiveness. It is computed based on the following formula:

Ewm = EcPV*Wecpv+EnPV*Wenpv+SoPV*Wsopv

Where: Ewm – Effectiveness of C&D waste management;

EcPV – Economic performance value of C&D waste management;

EnPV – Environmental performance value of C&D waste management;

SoPv – Social performance value of C&D waste management;

Wecpv – Weight of EcPV;

Wenpv – Weight of EnPV

Wsopv – Weight of SoPV.

In the present case, each variable of Wecpv, Wenpc and Wsopv is equally assigned with a value of 1/3. Results show that the value of Ewm in the 1st month is -3.23, and then it increases to 12.95 in the 2nd month. In the 3rd month, it subjects to a small decline due to decreases in both EcPV and EnPV. After that, Ewm presents a general trend of increase, amounting to a value of 22.78 in the 18th month. Although the value of Ewm is positive at the end of the project, it should be pointed out the effectiveness of C&D waste management of the project under study is relatively lower compared to best standard of 100 and needs to be further improved.

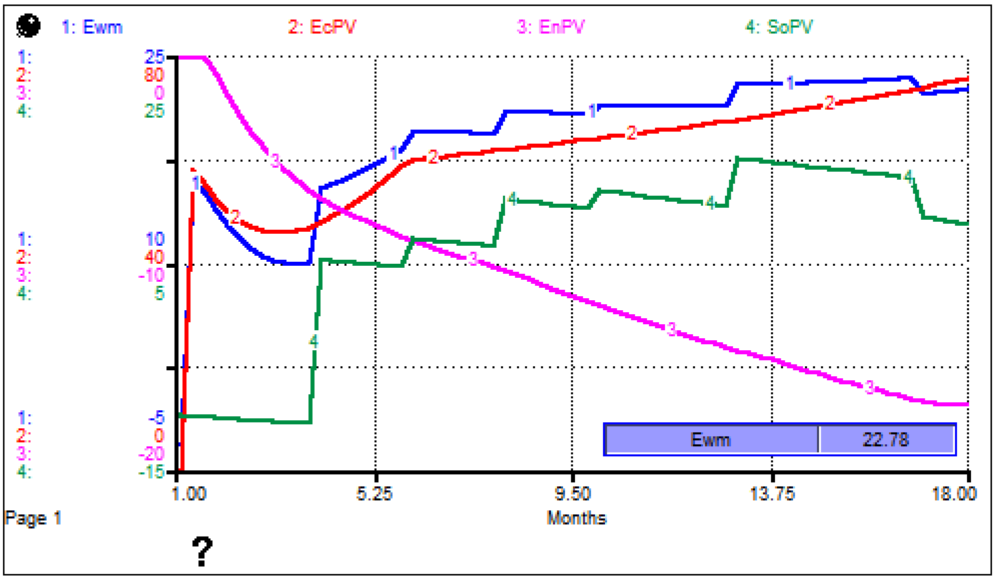

Figure 6.12: Overall results of the effectiveness of C&D waste management

6.7 Summary

Based on the established dynamic model for evaluating the effectiveness of C&D waste management developed in the former chapter, this chapter detailed the model application process based on a real case. The majority of data were collected through site survey and a series of formal and informal interviews and meetings. Various methods were employed to quantify variables built in the model. Results of the model validation determined that the proposed model is robust and credible to use. Finally, detailed simulation results of the case were analyzed and discussed. It was found that the project under the study obtained a value of 22.78 for its effectiveness of C&D waste management activities, indicating a relatively lower effectiveness in managing the C&D waste, in comparison with the best standard of 100.

Although the chapter presented base run simulation results, measures for improving the effectiveness of C&D waste management were not considered. Therefore, the following chapter focuses on scenario analysis, which examines how to improve the effectiveness of C&D waste management in terms of economic performance, environmental performance, and social performance by using different management measures. This is performed by simulating different conceived scenarios. Simulation results are then compared with those of the base run so that best scenarios can be identified.

CHAPTER 7 Simulation Scenario Analysis on the Effectiveness of C&D Waste Management

7.1 Introduction

7.2 Impacts of weightings between the attributes of economic, social and environmental performance

7.3 Analysis on single-policy scenarios for managing C&D waste

7.4 Analysis on multi-policy scenarios for managing C&D waste

7.5 Summary

7.1 Introduction

The previous chapter illustrated explicitly the application of the dynamic model developed for this research by using data collected from a construction project in Shenzhen city, South China. The rigorous validation procedure for SD model testing ensured the creditability of the model; while the simulation results of the studied case provided helpful insights into the construction project's effectiveness of C&D waste management in terms of economic performance, environmental performance, and social performance. Although the previous chapter provided a comprehensive explanation of using the model for assessing the effectiveness of C&D waste management in construction projects, it did not explain how the dynamic model could serve as an experimental platform to simulate effects of different management policies on the effectiveness of C&D waste management; this chapter does precisely that.

The following section exhibits simulation results by considering different combinations between Wecpv (weight of economic performance), Wenpv (weight of environmental performance) and Wsopv (weight of social performance). These provide insights into how the effectiveness of C&D waste management of the same construction project will change when the three dimensions, namely, economic performance, environmental performance, and social performance, are perceived differently by different decision-makers.

Afterwards, a series of management policy scenarios are designed based on a review of related literature, and simulations are carried out by applying these scenarios. Results of each of the designed scenarios are compared with results of the base run in Chapter 6 and recommendations for improving the effectiveness of C&D waste management of the studied project are proposed.

7.2 Impacts of weightings between the attributes of economic, social and environmental performance

In the subsystem of 'effectiveness of C&D waste management' as shown in Figure 5.36, Ewm (effectiveness of C&D waste management) is determined by the economic performance, environmental performance and social performance of C&D waste management and therefore calculated through the following formula:

$$\mathbf{Ewm} = [EcPV, EnPV, SoPV][Wecpv, Wenpv, Wsopv]^T$$

$$= EcPV*Wecpv + EnPV*Wenpv + SoPV*Wsopv$$

Where Ewm is the overall effectiveness of C&D waste management, EcPV is the economic performance value of C&D waste management, EnPV is the environmental performance value and SoPV is the social performance value. Wecpv, Wenpv and Wsopv are the weights of EcPV, EnPV and SoPV respectively; the total value of the three weights is equal to 1.

In the base run, a value of 1/3 was equally assigned to each of the weighting variables. However, different situations might exit in practice. For example, the economic performance of C&D waste management would be perceived as more important by some decision-makers when evaluating the effectiveness of C&D waste management, while the social performance would be regarded as more critical by other decision-makers. Also, previous study by Lu and Yuan (2010) revealed that environmental issues were on a relatively lower agenda when managing C&D waste management in China, compared to concern over economic and social performance. In this regard, decision-makers' different perceptions of values of these weighting variables will to a large extent influence the assessment results. This section therefore investigates the effectiveness of C&D waste management by applying different combinations between Wecpv, Wenpv and Wsopv.

In addition to the base run (*Wecpv = Wenpv = Wsopv = 1/3*), three other scenarios concerning the three weighting variables are considered, including:

(1) *Wecpv = 1/2, Wenpv = Wsopv = 1/4*, considering that the economic performance of performing C&D waste management is more important than related environmental and social performance by decision-makers;

(2) *Wsopv = 1/2, Wecpv = Wenpv = 1/4*, considering that the social performance is more important than economic and environmental performance by decision-makers; and

(3) *Wenpv* = *1/2*, *Wecpv* = *Wsopv* = *1/4*, considering that the environmental performance is more critical than economic and social performance by decision-makers.

Simulation results of the above four scenarios are shown in Figure 7.1 and Table 7.1.

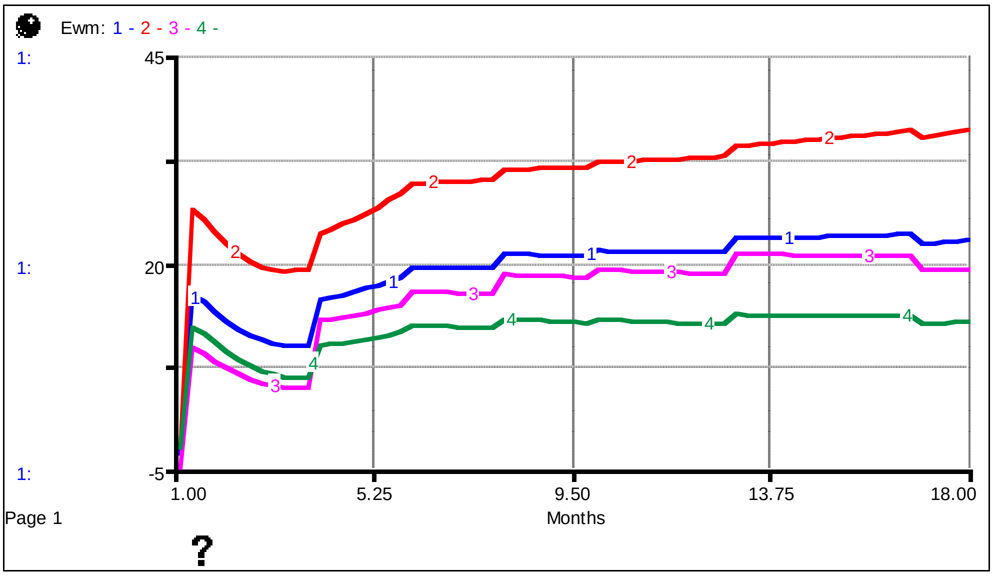

Figure 7.1: Simulation results of Ewm by adopting different weightings

Table 7.1: Simulation results of Ewm by adopting different weightings

Table 11 ()

Months	1: Ewm	2: Ewm	3: Ewm	4: Ewm
1.00	-3.23	-2.42	-4.84	-2.42
2.00	12.95	22.35	7.21	9.28
3.00	10.24	19.16	5.10	6.45
4.00	15.57	23.69	13.03	9.98
5.00	16.92	26.10	13.95	10.72
6.00	19.57	29.70	16.53	12.47
7.00	19.53	29.94	16.41	12.25
8.00	21.08	31.37	18.63	13.23
9.00	20.99	31.57	18.44	12.94
10.00	21.53	32.25	19.18	13.14
11.00	21.46	32.48	19.00	12.90
12.00	21.43	32.76	18.83	12.70
13.00	23.04	34.29	21.09	13.74
14.00	23.13	34.71	21.04	13.65
15.00	23.24	35.16	20.99	13.56
16.00	23.40	35.68	20.98	13.52
17.00	22.38	35.36	19.15	12.62
Final	22.78	36.15	19.32	12.88

Scenario 1: Wecpv = Wenpv = Wsopv = 1/3

Curve 1 in Figure 7.1 shows results of the effectiveness of C&D waste management of the studied project when the scenario of *Wecpv* = *Wenpv* = *Wsopv* = *1/3* is considered. It can be seen that except for a minor decrease in the 3rd month, the curve exhibits a general trend of increase. The value of Ewm at the end of the project is 22.78 under this scenario.

Scenario 2: Wecpv = 1/2, Wenpv = Wsopv = 1/4

Curve 2 in Figure 7.1 demonstrates results of Ewm when the scenario of *Wecpv* = *1/2, Wenpv* = *Wsopv* = *1/4* is applied. Based on the results listed in Table 7.1, it can be observed that values of Ewm in scenario 2 are higher than those in scenario 1 throughout the project duration, indicating that the effectiveness of C&D waste management in the construction project will be better when the economic performance is given a higher weight. Ewm finally receives a value of 36.15 under this scenario.

<u>Scenario 3: Wsopv = 1/2, Wecpv = Wenpv = 1/4</u>

Results of the scenario (Wsopv = 1/2, Wecpv = Wenpv = 1/4) is depicted by Curve 3 in Figure 7.1. It shows that from the 4th to 10th months, Ewm will increase gradually, although having a lower increasing rate compared to scenario 1 and scenario 2. At the end of the project, Ewm receives a value of 19.32.

<u>Scenario 4: Wenpv = 1/2, Wecpv = Wsopv = 1/4</u>

In this scenario, the environmental performance is perceived as more important with a weight of 1/2, while each weight of the economic and social performance is assigned a value of 1/4. The results (see Curve 4 in Figure 7.1) indicate that from the 4th month onward, Ewm will get the lowest values over the project duration under this scenario, compared to its values under the other three scenarios. Meanwhile, a further examination of values of Ewm during the 4th and 18th month implies that Ewm will have the lowest increasing rate when the environmental performance is regarded as more important, evidenced by the value of Ewm 12.88 in the end of the project, .

In summary, the above results demonstrate clearly that the construction project will get the highest value in Ewm when the economic performance of performing C&D waste management is considered as more important, while Ewm will receive the lowest value when the environmental performance is perceived as more important. This to some extent helps explain why current construction practice in China treats economic performance as a priority when developing and implementing a C&D waste management plan.

7.3 Analysis on single-policy scenarios for managing C&D waste

An extensive examination of the literature indicates that a wide range of management policies have been presented by researchers (e.g. Yuan et al., 2011; Lu and Yuan, 2010; Wang et al., 2008, 2010) for promoting the effectiveness of C&D waste management in China, typically including:

- Promoting the effectiveness of C&D waste management regulations;
- Raising practitioners' awareness about C&D waste minimization through vocational training and education;
- Launching an appropriate C&D waste disposal charging fee;
- Adopting low-waste construction technologies;
- Promoting public satisfaction about C&D waste management, and

- Reducing design changes.

Based on these policies, three single-policy scenarios are designated accordingly for discussion, encompassing:

Scenario 5: Increasing C&D waste disposal charging fee;

Scenario 6: Improving regulatory environment for managing C&D waste;

Scenario 7: Promoting public satisfaction about C&D waste management.

It should be highlighted that the three scenarios are developed only for illustration in this study; other scenarios, such as reducing design changes, can also be simulated in the future to test how the reduction of project design changes could affect the effectiveness of C&D waste management. Furthermore, it should also be noted that in each of the three scenarios, only one policy variable is altered for simulation while other variables are unchanged as they are in the base run. Simulation results of the three single-policy scenarios are discussed in the following section.

Scenario 5: Increasing C&D waste disposal charging fee

In this scenario, the consideration is given to the change of waste disposal charging fee while assuming other variables remain unchanged. Imposing charges for C&D waste dumping under the 'Polluter-Pays-Principle' is generally considered to be an effective measure for reducing waste generation (Tam, 2008a; Kibert et al., 2000). Although this policy has been implemented in Shenzhen, the charge for dumping into landfills there is significantly less than it is in other jurisdictions. For example, in 2008 the charge in Shenzhen was approximate 6Yuan (US$0.87) per ton (Yuan, 2008) as compared to HK$125 (US$16.13) per ton in Hong Kong (Hao et al., 2008a). A study conducted by Lu and Yuan (2010) revealed that when the rate rises to 80-100Yuan (US$11.68-US$14.60) per ton, more than 90% of respondents are willing to reduce C&D waste by various methods other than dumping directly into landfills. Experiences in other regions have also shown that market-based instruments, such as incentive or C&D waste charging schemes, are more effective in managing C&D waste (Duran et al., 2006; Craighill and Powell, 1999).

In view of the relatively low C&D waste landfill charging fee in Shenzhen, this scenario is devised to test how an increased waste landfill charging fee can contribute to promoting the effectiveness of C&D waste management. Three simulations are performed in this scenario to understand the effect of this policy change. The first simulation is the base run, in which the value of ULC (unit landfilling charge) is 6Yuan (**coded as 5A**). In the second run, a higher value of 15Yuan per ton (**coded as 5B**) is assigned to ULC. In the third run, ULC receives the highest value of 25Yuan per ton (**coded as 5C**). Results of each of the three simulations are represented by Curve 1, Curve 2 and Curve 3 respectively, as shown in Figure 7.2.

It is clear that along with the ULC increases, the effectiveness of C&D waste management (Ewm) for the studied project decreases. By the end of the project, the variable of Ewm will gain a value of 22.78, 19.98 and 15.52 respectively under the three simulations on changing the waste disposal charging fee. This demonstrates that with other policies unchanged, if current C&D waste disposal charging fee is increased to 25Yuan per ton, the effectiveness of C&D waste management of the studied project will be decreased by 30.4%.

A further examination of the economic performance (EcPV), environmental performance (EnPV) and social performance (SoPV) of C&D waste management indicates that variation of ULC will bring significant influence to EcPV, moderate changes to EnPV and almost no effect on SoPV. Specifically, when ULC is promoted from 6Yuan/ton to 25Yuan/ton, EcPV will decrease from 76.26 to 68.94 (a decreasing rate of 9.6%), EnPV will increase from -16.85 to -16.56 (an increasing rate of 1.7%), and SoPV will change from 8.93 to 8.88 (a slim changing rate of -0.6%), at the end of the project. This implies that policies relating to C&D waste disposal charging fee can significantly affect the economic performance of C&D waste management of the project, while leading to minor effects on the environmental and social performance. The results also suggest that if the local authority attempts to adopt waste disposal charging fee alone for managing C&D waste, the effectiveness of C&D waste management of construction projects will eventually decrease; in other words, changing waste disposal charging fee must be complemented by other policies for promoting the effectiveness of C&D waste management.

Scenario 6: Improving regulatory environment for managing C&D waste

In this scenario, the consideration is given to the change of regulatory environment while assuming other variables remain unchanged. Regulatory environment for managing C&D waste herein refers to a policy system formulated by various C&D waste management regulations, as well as the effective operation of the policy system in practice. It has been acknowledged that better regulatory environment is critical to the implementation and promotion of C&D waste management practices in any given countries/regions as government generally plays a central role in promoting C&D waste management practices by enforcing policies for the whole industry and supervising their implementation (Jaillon and Poon, 2008; Karavezyris, 2007)

To date, many economies have regulations in place to deal with C&D waste management problems. For example, The US government has promulgated the Leadership in Energy and Environmental Design (LEED) certification system to encourage diverting C&D waste by awarding points for diverting at least 50% of waste (US Green Building Council, 2008). The Hong Kong government has issued a series of regulations over the past two decades for minimizing C&D waste, typically including adopting a waste disposal ordinance, launching a green manager scheme, drafting a waste reduction framework, commissioning a pilot concrete recycling plant, stimulating the implementation of a waste-management-plan method, and promoting a public landfill charging scheme (HK Government, 2006). However, existing regulations in some developing countries are poorly executed, such as China (Lu and Yuan, 2010) and Thailand (Kofoworola and Gheewala, 2009). In such cases, major stakeholders' compliance with C&D waste management regulations will be important to the effective implementation of C&D waste reduction. Hence, this scenario is designed to examine how construction project stakeholders' efficiency of compliance with C&D waste management regulations can affect the effectiveness of C&D waste management.

For illustration, three simulations are designed under this scenario, which are tabulated in detail in Table 7.2. By running the model in line with the three groups of inputs of ECWR, results regarding the effectiveness of C&D waste management can be obtained, as shown in Figure 7.3. In the Figure, Curve 1 shows results of the base run, Curve 2 shows results of Run 2, and Curve 3 represents results of Run 3.

Table 7.2: Values of ECWR in three simulations

Month	Base run (6A)	Run 2 (6B)	Run 3 (6C)
1	13.00	13.00	13.00
2	15.20	17.40	19.60
3	17.40	21.80	26.20
4	19.60	26.20	32.80
5	21.80	30.60	38.80
6	24.00	35.00	44.50
7	26.20	38.80	48.70
8	28.40	42.60	52.70
9	30.60	45.90	56.30
10	32.80	48.70	59.13
11	35.00	51.50	61.08
12	36.90	53.90	63.02
13	38.80	55.40	64.67
14	40.70	56.60	66.03
15	42.60	57.83	67.38
16	44.50	59.13	68.63
17	45.90	60.42	69.38
18	47.30	61.73	70.13

It can be seen from Figure 7.3 that in the first nine-month period, there is no significant difference among values of Ewm in the three simulation runs. But from the tenth month onward, the three curves develop with different increasing rate. Specifically, Ewm in Run 3 begins to increase with the highest rate, while Ewm in the base run changes with the least increasing rate. Eventually, values of

Ewm for the base run, Run 2 and Run 3 are 22.78, 28.27 and 30.23 respectively. This indicates that changing of regulatory environment will affect the effectiveness of C&D waste management in a positive way. In other words, the better the regulatory environment for managing C&D waste, the higher the effectiveness of C&D waste management.

A closer look at the simulation results of EcPV, EnPV and SoPV (see Figure 7.3) show that changing of regulatory environment will influence EcPV and EnPV significantly but lead to slight influence on SoPV. Particularly, improving the regulatory environment for managing C&D waste will enhance the economic performance of C&D waste management of the project while reduce the environmental performance.

<u>Scenario 7: Promoting public satisfaction about C&D waste management</u>

In this scenario, the consideration is given to the change of public satisfaction about C&D waste management while assuming other variables remain unchanged. Public satisfaction with C&D waste management is an essential component affecting the social performance of waste management activities. The significance of public satisfaction has been explicitly discussed in Chapter 3. This scenario is launched to test how improvements in public satisfaction (variable of PS in the model) can influence the effectiveness of C&D waste management of the project. Simulations are carried out in line with three groups of inputting values of PS as listed in Table 7.3.

Table 7.3: Values of PS in three simulations

Month	Base run (7A)	Run 2 (7B)	Run 3 (7C)
1	12.00	22.00	32.00
2	9.36	19.36	29.36
3	6.82	16.82	26.82
4	25.65	35.65	45.65
5	23.28	33.28	43.28
6	24.68	34.68	44.68
7	22.35	32.35	42.35
8	26.26	36.26	46.26
9	23.93	33.93	43.93
10	24.10	34.10	44.10
11	21.78	31.78	41.78
12	19.46	29.46	39.46
13	23.40	33.40	43.40
14	21.08	31.08	41.08
15	18.76	28.76	38.76
16	16.45	26.45	36.45
17	9.13	19.13	29.13
18	6.81	16.81	26.81

Simulation results are illustrated in Figure 7.4. As can be seen, Ewm will be promoted when the public satisfaction for managing C&D waste improves, evidenced by values of Ewm in the base run, Run 2 and Run 3 are 22.78, 24.30 and 25.27 respectively at the end of the project. This demonstrates that promoting public satisfaction can improve the effectiveness of C&D waste management on a project.

Furthermore, it can be found that changes of PS will only lead to significant influence on SoPV while both EcPV and EnPV have little change. This shows that promoting public satisfaction can be a potential measure for improving the social performance.

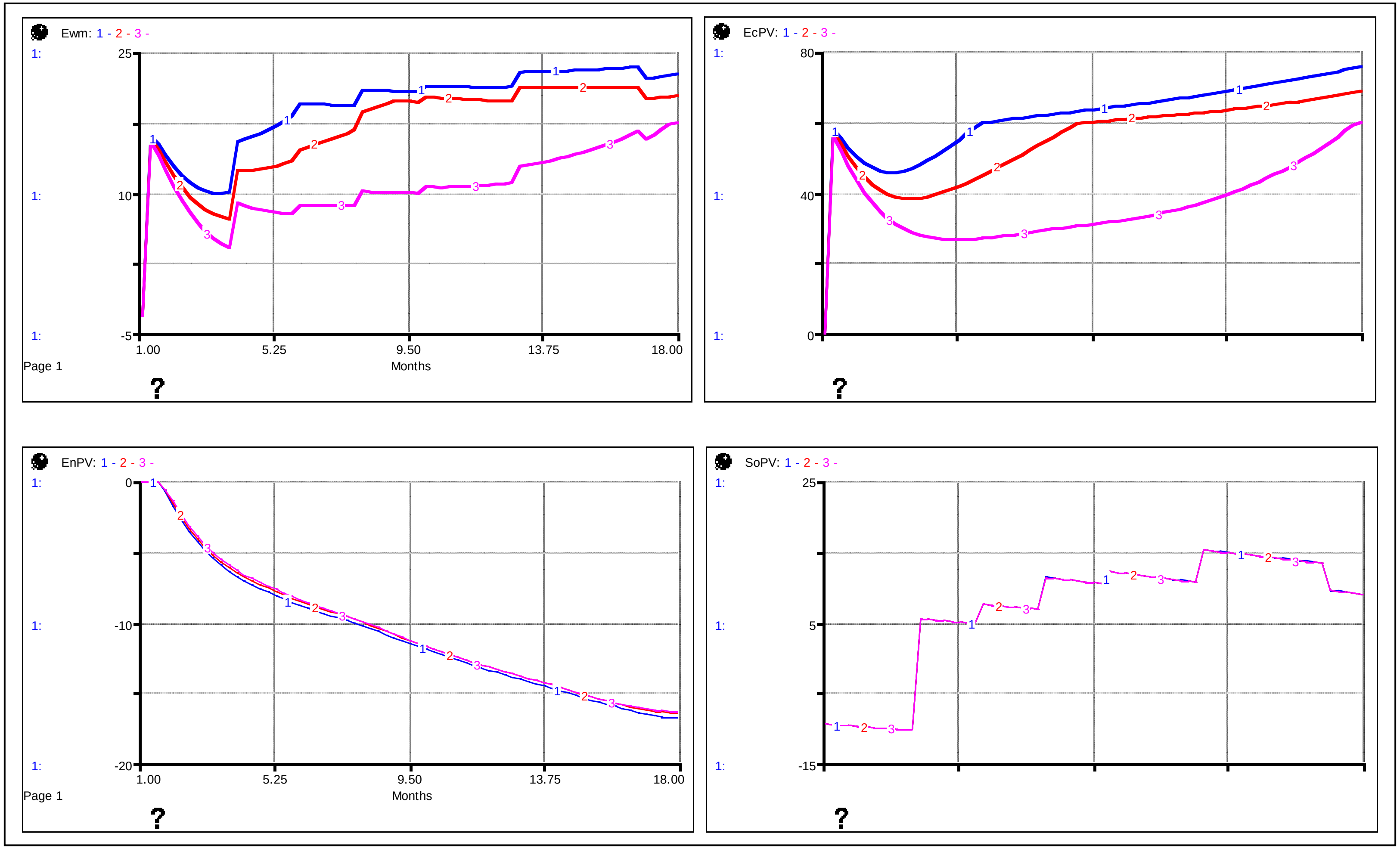

Figure 7.2: Simulation results of Scenario 5

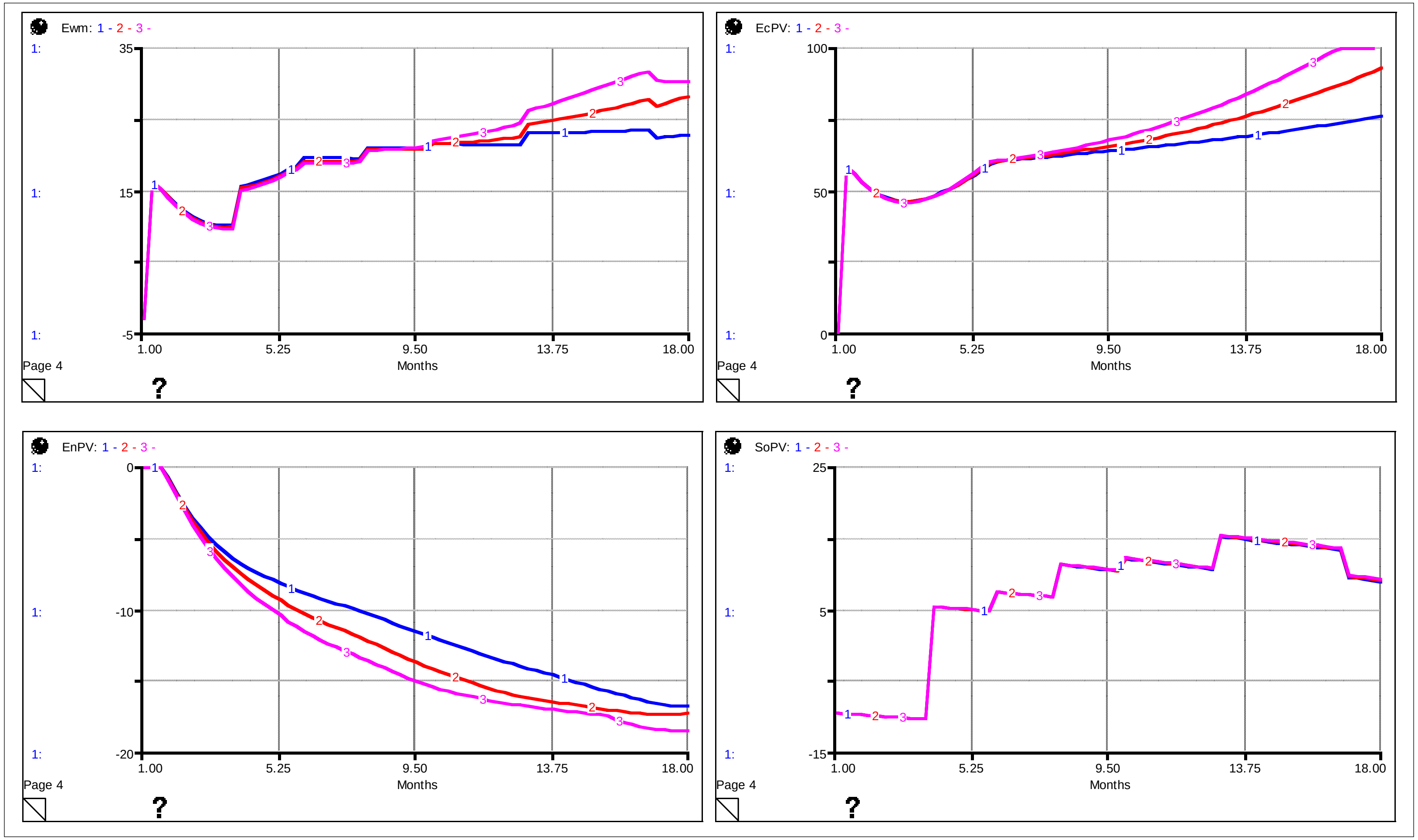

Figure 7.3: Simulation results of Scenario 6

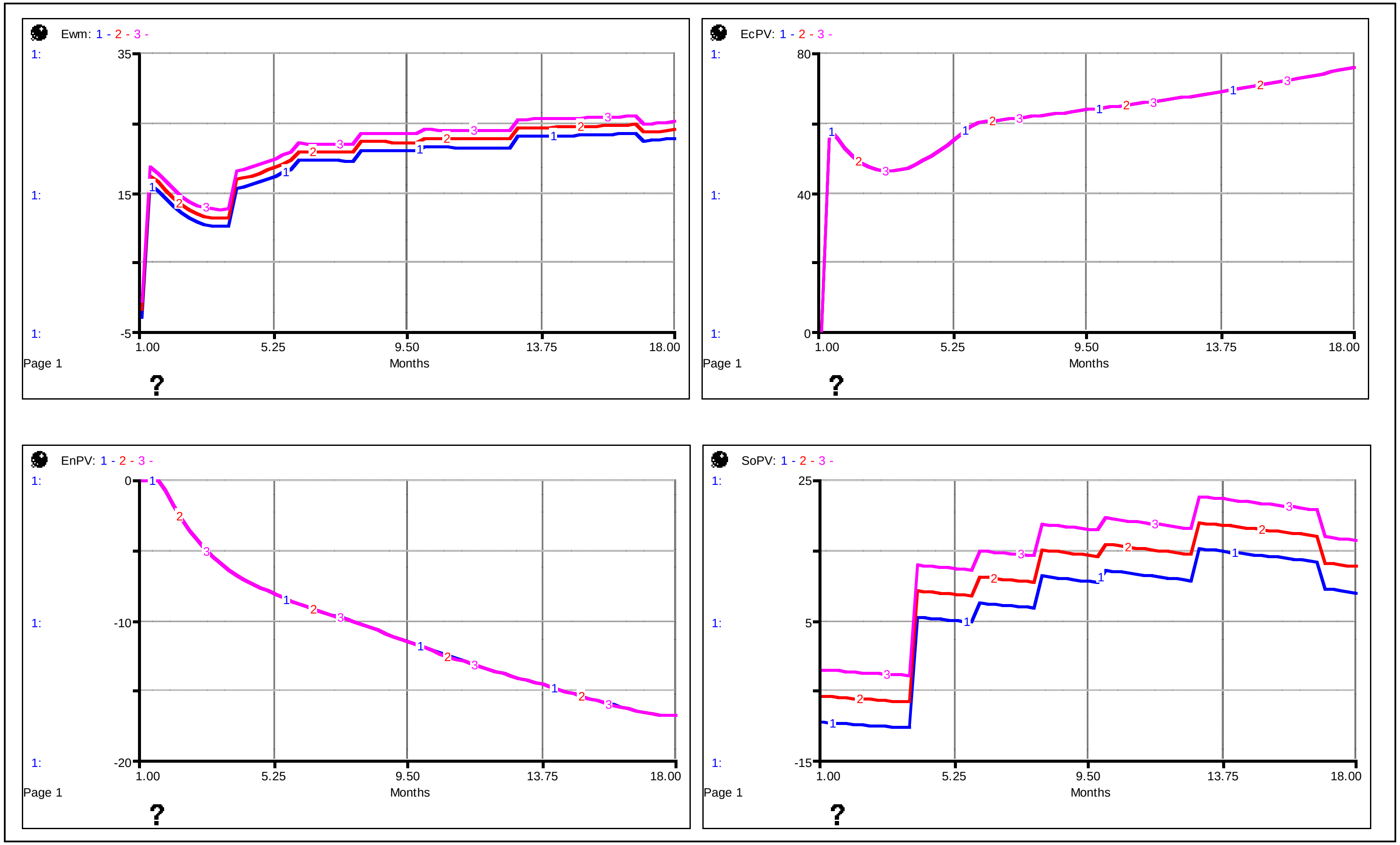

Figure 7.4: Simulation results of Scenario 7

7.4 Analysis on multi-policy scenarios for managing C&D waste

Assuming that all the three policy measures discussed in previous section (i.e. increasing the waste disposal charging fee, improving the regulatory environment for C&D waste management, and promoting the public satisfaction about C&D waste management) are taken at the same time for managing C&D waste in the project, 20 multi-policy scenarios can be formed accordingly, i.e. [5A, 6B, 7B], [5A, 6B, 7C], [5A, 6C, 7B], [5A, 6C, 7C], [5B, 6A, 7B], [5B, 6A, 7C], [5B, 6B, 7A], [5B, 6B, 7B], [5B, 6B, 7C], [5B, 6C, 7A], [5B, 6C, 7B], [5B, 6C, 7C], [5C, 6A, 7B], [5C, 6A, 7C], [5C, 6B, 7A], [5C, 6B, 7B], [5C, 6B, 7C], [5C, 6C, 7A], [5C, 6C, 7B], [5C, 6C, 7C]. In these scenarios, '5A' refers to the policy adopted in the first simulation run of Scenario 5, '6C' refers to the policy applied in the third simulation run of Scenario 6, and so forth. Detailed simulation results of applying these multi-policy scenarios are tabulated in Table 7.4.

Table 7.4: Simulation results of Ewm under multi-policy scenarios

Month	3	6	9	12	15	18
Base run [5A, 6A, 7A]	10.24	19.57	20.99	21.43	23.24	22.78
[5A, 6B, 7B]	10.51	19.55	21.17	22.56	26.36	28.69 (+25.9%)*
[5A, 6B, 7C]	10.93	19.96	21.59	22.97	26.78	29.10 (+27.2%)
[5A, 6C, 7B]	10.32	19.20	21.29	23.97	19.57	30.65 (+34.5%)
[5A, 6C, 7C]	10.73	19.62	21.71	24.39	29.98	31.07 (+36.4%)

[5B, 6A, 7B]	8.58	15.02	20.27	20.37	21.74	20.84 (-8.5%)
[5B, 6A, 7C]	9.00	15.42	20.69	20.78	22.15	21.25 (-6.7%)
[5B, 6B, 7A]	8.05	14.73	19.81	20.82	24.19	26.15 (+14.8%)
[5B, 6B, 7B]	8.47	15.15	20.22	21.23	24.60	26.56 (+16.6%)
[5B, 6B, 7C]	8.89	15.56	20.64	21.65	25.02	26.98 (+18.4%)
[5B, 6C, 7A]	7.90	15.16	20.01	22.31	27.60	30.38 (+33.4%)
[5B, 6C, 7B]	8.32	15.57	20.43	22.72	28.02	30.80 (+35.2%)
[5B, 6C, 7C]	8.73	15.99	20.85	23.14	28.44	**31.21 (+37.0%)**
[5C, 6A, 7B]	6.29	9.06	10.52	11.26	14.79	17.96 (-21.2%)
[5C, 6A, 7C]	6.71	9.47	10.93	11.67	15.20	18.37 (-19.4%)
[5C, 6B, 7A]	5.79	9.07	14.15	19.19	21.99	23.48 (+3.1%)
[5C, 6B, 7B]	6.21	9.49	14.57	19.60	22.41	23.89 (+4.9%)
[5C, 6B, 7C]	6.63	9.91	14.99	20.02	22.82	24.31 (+6.7%)
[5C, 6C, 7A]	5.68	9.80	18.93	20.75	25.61	29.24 (+28.4%)
[5C, 6C, 7B]	6.10	10.21	19.34	21.17	26.03	29.66 (+30.2%)
[5C, 6C, 7C]	6.51	10.63	19.76	21.57	26.44	30.08 (+32.0%)

Note: Percentages in the bracket show the variation of values of each variable compared to that obtained in the base run.

As analyzed previously, when single-policy scenarios for managing C&D waste are applied in the project, highest values of Ewm will occur while adopting measures of 5A, 6C and 7C respectively. It therefore seems that the multi-policy scenario comprising 5A, 6C and 7C would result in the highest value of Ewm. However, it is surprising to see from Table 7.4 that among all the multi-policy scenarios, [5B, 6C, 7C] is the one leading to the highest value of Ewm, achieving an increase rate of 37.0% compared with the Ewm obtained in the base run. Meanwhile, the value of Ewm by applying the policy scenario of [5B, 6C, 7C] is larger than any of those obtained in single-policy scenarios. It can therefore be concluded that among all policy scenarios investigated in this study, the best solution to the promotion of effect C&D waste management for the project is increasing the current waste disposal charging fee to 15Yuan per ton, and simultaneously deploying measures corresponding to 6C and 7C, which are detailed in Table 7.2 and Table 7.3, respectively.

7.5 Summary

Following the case study carried out in the previous chapter, this chapter conducted a series of policy analysis for promoting the effectiveness of C&D waste management in the case study project. Scenarios for policy analysis were mainly designed in line with three aspects: the first aspect was exploring how Ewm would change by adopting different combinations between weightings, namely, Wecpv, Wenpv and Wsopv. The second aspect was examining how Ewm would alter when the project was implemented under three single-policy scenarios, including increasing C&D waste disposal charging fee, improving the regulatory environment for managing C&D waste, and promoting public satisfaction about C&D waste management. And the final aspect was an investigation of how Ewm would change under 20 multi-policy scenarios, which were all produced by combining the three policies used in the single-policy scenarios.

The results of adopting different value combinations of Wecpv, Wenpv and Wsopv showed that the value of Ewm would be the highest if the economic performance of C&D waste management was given more attention in the project. Furthermore, Ewm would receive the lowest value if the environmental performance was considered as more important than the other two dimensions by decision-makers of the project. Although the same project would receive different values of Ewm when different combinations of Wecpv, Wenpv and Wsopv were applied, this kind of scenario analysis enabled the decision-makers to further their understanding of the effectiveness of C&D waste management, and more importantly, could serve as a tool for evaluating Ewm of the project according to the understanding and perception of each decision-maker in the project.

The simulation results of single-policy scenarios indicated that increasing the C&D waste disposal charging fee would affect Ewm in a negative way, while improving regulatory environment and promoting public satisfaction with C&D waste management would both contribute to the promotion of Ewm positively.

Furthermore, the simulation results of multi-policy scenarios demonstrated that among all the scenarios discussed, the effectiveness of C&D waste management could be increased from 22.78 in the base run to 31.21 (a increasing rate of 37.0%) by adopting the management policy combination of [5B, 6C, 7C].

Simulation results of scenario analysis performed in this chapter could provide valuable insights into the improvement of Ewm for the studied project. Although the analyzed scenarios do not involve all management policies that can be potentially adopted, the process of scenario development and results analysis would be very useful for carrying out similar scenario analyses by using the developed model in the future. It also provides a methodology and tool for guiding C&D waste management effectiveness assessment in general.

Chapter 8 Conclusions

8.1 Introduction

This chapter presents the conclusion of this research. The research objectives are reviewed, followed by a summary of key conclusions achieved through undertaking this study. The contributions, significance and limitations of the research are also indicated, and the thesis concludes by suggesting areas for further research.

8.2 Review of research objectives

A huge amount of C&D waste is generated by construction activities every year around the globe. C&D waste along with its associated adverse impact on the environment and society has become an issue attracting widespread attention from both industry practitioners and researchers. C&D waste management is now a research discipline in its own right. This study opines that effective C&D waste management should embrace the harmonious achievement of the economic performance, environmental performance and social performance related to C&D waste management. However, it was determined by a review of the literature that there is a lack of a tool for assessing the effectiveness of C&D waste management systems by collectively taking account of associated economic, environmental and social performance. Thus the overall aim of this research was:

- To develop a dynamic model for assessing the effectiveness of C&D waste management systems.

In order to achieve the above aim, four objectives needed to be completed, which were:

(1) To identify major variables affecting the effectiveness of C&D waste management systems;

(2) To construct a dynamic model for evaluating the effectiveness of C&D waste management systems;

(3) To validate the established model and demonstrate its application; and

(4) To analyze a series of management scenarios for improving the effectiveness of C&D waste management systems.

8.3 Major conclusions

This study developed a dynamic model for assessing the effectiveness of C&D waste management to help the construction industry manage waste more effectively. The research objectives have been achieved, including: (1) the identification of major variables affecting the effectiveness of C&D waste management; (2) the development of a dynamic model for assessing the effectiveness of C&D waste management; (3) the validation and application of the established model; and (4) the management policy scenario analyses for improving C&D waste management for the selected case. By accomplishing the research objectives, conclusions scattered throughout the thesis have been drawn. They can be summarized as follows.

(1) Current practices of C&D waste management should be further enhanced

C&D waste resulting from construction activities has been a major cause of pollution. It depletes the finite land resources for waste landfill, contaminates the environment by negatively affecting air and water quality, and endangers the society in a number of ways. To deal with the increasingly severe problem, an abundance of studies have been undertaken to investigate a broad array of issues relating to C&D waste management over the past few decades. Undoubtedly, these research outputs have played an important role in advancing the practices of C&D waste management worldwide. However, a critical review of the literature, presented in Chapter 2, suggests that the current effectiveness of C&D waste management is on the whole limited and therefore needs to be further enhanced.

(2) There is a need to better assess the effectiveness of C&D waste management

Before improvements in current C&D waste management practices can be realized, it is essential to assess such practices effectively and efficiently. Although efforts have been made to assess C&D waste management, the relevant literature reveals some notable limitations, including: (a) current assessment research have treated C&D waste processes (such as C&D waste generation, reuse, recycling, and disposal) separately; (b) elements in different C&D waste management processes are largely considered as independent; and (c) existing studies have mainly been carried out from a static point of view.

However, recent research has indicated that C&D waste management is actually a complicated system involving a number of elements which are largely interdependent. Also, C&D waste management systems are dynamic, which means that the overall effectiveness of C&D waste management will be varying across the whole lifecycle of construction projects. Therefore, there is a need to better understand and assess the effectiveness of C&D waste management by envisaging these characteristics such as the interdependence and dynamics.

(3) System dynamics is an effective approach for this study, by which the economic performance, environmental performance and social performance of C&D waste management can be collectively investigated

Although C&D waste management activities influence three aspects of performance, namely, economical, environmental, and social, very few studies have evaluated C&D waste management by collectively integrating the three aspects. To a large extent the three aspects have not been equally emphasized with most research having focused on economic performance and very little on environmental and social performance. To fully assess the effectiveness of C&D waste management, the three dimensions of C&D waste management should be holistically investigated. The system dynamics approach was identified as an appropriate approach for this purpose.

(4) Importance of understanding major variables affecting the effectiveness of C&D waste management

In line with the principle that the economic performance, environmental performance and social performance should be harmoniously promoted when developing effective C&D waste management, major variables affecting the effectiveness of C&D waste management have been identified, which are tabulated in Table 3.2 in Chapter 3. These variables not only facilitate a comprehensive understanding of the effectiveness of C&D waste management and lay a solid foundation for model development in this study, but also can be useful references for future studies with similar research intention.

(5) A dynamic model is significance for assessing the effectiveness of C&D waste management

The model developed by using SD can overcome the limitations observed in existing literature, functioning as a useful and effective tool for better assessing the effectiveness of C&D waste management. Particularly, the dynamic nature of C&D waste management system and the interrelationships among the variables in the system have been well embodied and examined by using the dynamic model. The process of conceptual model development, in which interrelationships inherent in the identified variables are portrayed through a series of causal loop diagrams, provides valuable insights into understanding how the major variables are interrelated to form the entire system. The stock-flow diagram, depicted with the aid of the iThink software package, makes it easier and more efficient to simulate the system on a computer in order to investigate how the overall effectiveness of C&D waste management system would dynamically change in the simulation period.

(6) The model developed is applicable and effective for assessing the effectiveness of C&D waste management

The developed model involves three types of variables: (a) quantitative variables, (b) qualitative variables, and (c) constant variables. Different methods were employed in this study to ensure that each type of the variables was properly quantified. The validation of the model evidently demonstrates that the model is robust and can reasonably mirror the real-world situation. Furthermore, the simulation results obtained from the base run provide a good deal of information for deepening decision-makers' understanding of how the effectiveness of C&D waste management alters throughout the waste chain.

(7) Scenario analysis provides an experimental platform for simulating management policies for managing C&D waste

By carrying out a series of scenario analyses, it shows clearly that the dynamic model is capable of being used as an experimental platform to simulate effects of different management policies on the overall effectiveness of C&D waste management over the whole waste chain, so that best management policies can be identified.

Simulation results obtained by considering different value combinations of Wecpv (weight of economic performance), Wenpv (weight of environmental performance) and Wsopv (weight of social performance), reveal that the effectiveness of C&D waste management on the same construction project varies greatly when the three performance dimensions (economic, environmental, and social) are weighted differently by different decision-makers. This helps explain why different decision-makers have disparate understandings about the effectiveness of C&D waste management.

The process of designing policy scenarios affords a detailed guideline on developing simulation scenarios based on the dynamic model. Furthermore, the results of policy scenario analyses are very informative for enlightening promising measures to ameliorate the effectiveness of C&D waste management of the studied project.

8.4 Contributions

(1) Contributions to the body of knowledge of C&D waste management

The study has constructed a simulation model, which integrates all essential variables highly related to the effectiveness of C&D waste management. These variables can be used as *an assessment indicator system* by future studies. The model itself is a first attempt to investigate the *interrelated variables* affecting the effectiveness of C&D waste management *from a holistic point of view*, which fills the gaps identified in the literature. All this contribute to the body of knowledge of C&D waste management.

(2) In-depth understanding about the system of C&D waste management

Through portrayal of the interrelationships between various variables, the interrelationships underlying C&D waste management systems can be better revealed. It will be very helpful for deepening researchers' and decision-makers' understanding of the complicated mechanism inherent in the C&D waste management systems.

(3) Provision of a new research tool

Through using the SD approach, the developed model provides a first attempt to collectively integrate the economic performance, environmental performance and social performance of C&D waste management. The result is a new and valuable research tool for assessing and improving the effectiveness of C&D waste management. The strengths of the new research tool include:

- Compared to conventional techniques for assessing C&D waste management, the SD model has the advantages of ease of model structure modification, ability to perform sensitivity analysis, and effective communication of simulating results.
- The model is effective and efficient when being used as a tool to simulate policy scenarios for identifying the best policy among alternatives and improving the effectiveness of C&D waste management.
- Although simulated by using data collected within the Chinese construction industry, the model's validation demonstrates that it is sufficiently generic in nature to be applied to construction projects in any other contexts simply by substituting the data in the model with the data of any given construction project.

(4) Provision of a practical tool for assessing the effectiveness of C&D waste management

This study offers a practical tool which enables contractors to test different management measures with ease before implementing them, without worrying about the possible negative impacts of doing so. By using the model, numerous attempts can be made to try out measures that may improve the effectiveness of waste management on construction projects.

(5) Provision of a platform for further debate

As mentioned above, this is the first attempt to investigate C&D waste management systems holistically, particularly for assessing and improving its effectiveness. In this regard, the study broadens the application of SD approach to the discipline of C&D waste management and provides a platform for further studies and debate.

8.5 Limitations and further research

(1) Limitations

The limitations of the model developed in this study are important for its broader application.

- The substantial number of interrelationships underlying the major variables makes it impossible to fully examine all the possible dynamic interactions. Furthermore, it was not practical to design, simulate and discuss all the possible policy scenarios for improving the effectiveness of C&D waste management.

- Due to resource limitations, it was only possible to collect data from one real-world project for testing and validating the model.

(2) Further research

Notwithstanding the limitations outlined above, this study has not only opened a new window onto assessing the effectiveness of C&D waste management it has also provided a basis for further research, which may include the following:

- Testing more policy scenarios on the model in order to investigate their effects on the effectiveness of C&D waste management.
- Enhancing the model's ability to mirror real-world situation by making adjustments to it based on data from more case studies.

APPENDICES

Appendix A: Descriptions on the data quoted in the model

Abbreviation	Variables
Subsystem of C&D waste generation	
AAWR	Accumulative amount of C&D waste reduction
AIIWM	Actual increasing rate of investment in C&D waste management
ALLWT	Application level of low-waste construction technologies
ALWT	Applying low-waste construction technologies
AWMCwO	Accumulated C&D waste management culture within an organization
CFAM	Constructed floor area monthly
CIWM	Changing of investment in C&D waste management
CIWR	Cost impacts on C&D waste reduction
CPWtRW	Changing of practitioners' willingness to reduce C&D waste
CTCCB	Changing of traditional construction culture and behavior
CWMCwO	Changing of C&D waste management culture within an organization
DDCs	Decreasing rate of occurrence frequency of design changes
ELALWT	Expected level of applying low-waste construction technologies by decision makers
EMfWRD	Effects of measures taken for C&D waste reduction in project design
EIRPWtRW	Expected increasing rate of practitioners' willingness to reduce C&D waste by decision makers
EtRW	Efforts to reduce C&D waste
FDCs	Frequency of occurrence of design changes
GEMW	Gaining experience of managing C&D waste
IALWT	Impacts of applying low-waste construction technologies
IDCs	Impacts of design changes on C&D waste reduction
IIWM	Impacts of investment in C&D waste management
IMCWR	Impacts of management capacity for C&D waste reduction
IPWtRW	Impacts of practitioners' willingness to reduce C&D waste
ISSL	Impacts of site space limit on C&D waste reduction
ITCCB	Improvements on traditional construction culture and behavior
IVTWM	Implementing in-house vocation training in C&D waste management

IWMCwO	Impacts of C&D waste management culture within an organization
IWM	Investment in C&D waste management
IWRAS	Improvements on C&D waste reduction awareness and skills
IWRC	Impacts of C&D waste reduction cost
MCWR	Management capacity for C&D waste reduction
PWRLC	Promotion of C&D waste reduction via landfilling charge
PWtRW	Practitioners' willingness to reduce C&D waste
RW	Reducing C&D waste
SALWT	Status quo of applying low-waste construction technologies
SSL	Limit of construction site space on conducting C&D waste management
TCfWR	Total cost of C&D waste collection and sorting for waste reduction
WMCwO	C&D waste management culture within an organization
WG	Total C&D waste generation
WGFA	Average C&D waste generation per floor area
WGM	C&D waste generation monthly
WGR	C&D waste generating rate
WRR	C&D waste reduction rate
Subsystem of economic performance	
A&CRF	The availability and capacity of facilities for C&D recycling
ACoW	Amount of collected C&D waste
AIDW	Amount of illegally dumped C&D waste
ARecW	Amount of recycled C&D waste
AReuW	Amount of reused C&D waste
ASW	Amount of sorted C&D waste
AUPNM	Average unit price of new construction materials
CHIDW	Cost of handling illegally dumped C&D waste
CoW	Collecting C&D waste
CWDL	Cost of C&D waste disposal at landfills
CWCo	Cost of C&D waste collection
CWCoM	Monthly cost of C&D waste collection
CWRec	Cost of C&D waste recycling
CWReu	Cost of C&D waste reuse
CWS	Cost of C&D waste sorting
CWSM	Monthly cost of C&D waste sorting
CWTfStL	Cost of C&D waste transportation from construction sites to landfills
DRIWD	Decreasing rate of illegal C&D waste dumping
EcPV	Economic performance value
ECWR	Efficiency of compliance with waste regulations
IDW	Illegal dumping of C&D waste

ILCR	Impacts of landfilling charge on C&D waste recycling
IRIWD	Increasing rate of illegal C&D waste dumping
MIMW	Project managers' incentives to manage C&D waste
MSvRec	Construction materials saved via recycling
MSvReu	Construction materials saved via reuse
NPWM	The net profit by conducting C&D waste management in the project under study
NPWMs	The standard value of net profit by conducting C&D waste management in the project under study
NPWMmax	The maximum net profit by conducting C&D waste management in the project under study
NPWMt	Intolerable net profit by conducting C&D waste management in the project under study
PIWD	Percentage of illegal C&D waste dumping
PWCo	Percentage of C&D waste collection
PWDL	Percentage of C&D waste disposed of at landfills
PWReu	Percentage of C&D waste reuse
PWRec	Percentage of C&D waste recycling
PWS	Percentage of C&D waste sorting
R	Regulations associated with C&D waste disposal
RC	Changing of regulations associated with C&D waste disposal
RecW	Recycling C&D waste
ReuW	Reusing C&D waste
RSWM	Revenue from selling waste materials
SCDRRM	Saving in cost of disposing of the recycled and reused materials, which otherwise will enter landfills directly
SCPRRM	Saving in cost of purchasing the recycled and reused materials, which otherwise will be replaced by purchasing new materials.
SCTRRM	Saving in cost of transporting the recycled and reused materials, which otherwise will be transported from construction sites to landfills directly
SW	Sorting C&D waste
TAMS	Total amount of construction materials saved via recycling and reuse
TBWM	Total benefit of C&D waste management
TCWM	Total cost of C&D waste management
TDfStL	Transportation distance from construction sites to landfills
TWfStL	Transporting C&D waste from construction sites to landfills
UCPM	Unit cost of purchasing new construction materials
UCTfStL	Unit cost of transporting waste from construction sites to landfills
UCWCo	Unit cost of C&D waste collection

UCWRec	Unit cost of C&D waste recycling
UCWReu	Unit cost of C&D waste reuse
UCWS	Unit cost of C&D waste sorting
ULC	Unit landfilling charge
UPID	Unit penalty paid due to illegal dumping
WDL	C&D waste disposed of at landfills
Subsystem of environmental performance	
AAPPV	Accumulated performance value of air pollution
AEIID	Accumulated environmental impacts of illegally dumped C&D waste on public living environment
ANEPV	Accumulated performance value of noise emission
AP	Air pollution by C&D waste management activities
APmin	The minimum satisfaction value set by decision-makers for air pollution caused by C&D waste management activities
APPVM	Performance value of air pollution monthly
APs	The standard value of air pollution caused by C&D waste management activities
APt	Intolerable value of air pollution caused by C&D waste management activities
APPV	Performance value of air pollution
AWQ	Accumulative water quality
EIID	Environmental impacts of illegally dumped C&D waste on public living environment
EnPV	Environmental performance value
INETfStL	Impacts of noise emission while transporting waste from construction sites to landfills
IAPfStL	Impacts of air pollution while transporting waste from construction sites to landfills monthly
IAPRec	Impacts of air pollution while recycling waste
IIWD	Impacts of air pollution while illegally dumping C&D waste
ILC	Impacts of land consumption due to waste landfilling
INECo	Impacts of noise emission while collecting waste
LAO	Landfill area occupied
MIAPfStL	Multiplier of impacts of waste transportation from construction sites to landfills
MIAPREc	Multiplier of impacts of air pollution while recycling waste
MIDW	Multiplier of environmental impacts of illegally dumped C&D waste on public living environment
MINECo	Multiplier of impacts of noise emission while collecting waste
MINETfStL	Multiplier of impacts of noise emission while transporting waste from construction sites to landfills
MIWReu	Multiplier of impacts of air pollution while reusing C&D waste

MWDL	Multiplier of C&D waste disposed of at landfills, for the purpose of transforming the unit from ton to m^2
NE	Noise emission by C&D waste management activities
NEmin	The minimum satisfaction value set by decision makers for noise emission caused by C&D waste management activities
NEPV	Performance value of noise emission
NEPVM	Performance value of noise emission monthly
NEs	The standard value of noise emission caused by C&D waste management activities
NEt	Intolerable value of noise emission set by decision makers in the project under study
TIDWtL	Transporting illegally dumped waste to landfills
Wap	Weight of impacts of air pollution
WEL	Amount of C&D waste entering landfills
Weiid	Weight of environmental impacts of illegally dumped C&D waste
WILC	Weighted impacts of land consumption due to waste landfilling
Wiwp	Weight of impacts of water pollution
Wlao	Weight of landfill area occupied
Wne	Weight of impacts of noise emission
WQ	Water quality after considering impacts by C&D waste
WQC	Changing of water quality monthly
WVAP	Weighted value of impacts of air pollution
WVEIID	Weighted value of environmental impacts of illegally dumped C&D waste on public living environment
WVNE	Weighted value of impacts of noise emission by C&D waste management activities
WVWQ	Weighted value of water quality
Subsystem of social performance	
AERIWD	Accumulated effects of regulating illegal C&D waste dumping behavior
AERIWDSI	Accumulated effects of regulating the influence of illegal C&D waste dumping on society image
AIPWE	Accumulated impacts of physical working environment during C&D waste management
AJO	Actual provision of job opportunities
APIMW	Actual practitioners' initiative to minimize C&D waste
CSO	Changing of operatives' safety condition in C&D waste management
CPIMW	Changing of practitioner' initiative to minimize C&D waste
CPWE	Changing of physical working environment in C&D waste management

EMaxJO	Expected maximum provision of job opportunities estimated by decision makers
EMinJO	Expected minimum provision of job opportunities estimated by decision makers
EPIMW	Expected level of practitioners' initiative to minimize C&D waste
IIDSI	Improving the influence of illegal C&D waste disposal on society image
ILH	Impacts of C&D waste management activities on practitioners' long-term health
LH	Practitioners' long-term health condition after considering impacts of C&D waste management activities
Month	Time (month)
OS	Safety of operatives in C&D waste management
OS2	Present operatives' safety in C&D waste management
OSs	The standard value of operatives' safety in C&D waste management
OSt	Intolerable value of operatives' safety in C&D waste management, which is set by decision-makers in the project under study
PARIWD	Public appeal for regulating illegal C&D waste dumping behavior
PIMW	Practitioners' initiative to minimize C&D waste
PS	Public satisfaction about C&D waste management performance
PViidsi	Performance value of regulating illegal C&D waste disposal to improve society image
PWE	Physical working environment in C&D waste management
RIWD	Regulating illegal C&D waste disposal in the project under study
SoPV	Social performance value
VJO	Value of provision of job opportunities
Wjo	Weight of provision of job opportunities
Wlh	Weight of practitioners' long-term health condition
Wos	Weight of operatives' safety in C&D waste management
Wpariwd	Weight of public appeal for regulating illegal C&D waste dumping behavior
Wpimw	Weight of practitioners' initiative to minimize C&D waste
Wridsi	Weight of regulating illegal C&D waste disposal to improve society image
Wps	Weight of public satisfaction about waste management performance
WPVos	Weighted performance value of operatives' safety in C&D

	waste management
WPVpariwd	Weighted performance value of public appeal for regulating illegal C&D waste dumping
WPVps	Weighted value of public satisfaction about waste management performance
WPVpwe	Weighted performance value of physical working environment in C&D waste management
WPVridsi	Weighted performance value of regulating illegal C&D waste disposal to improve city image
Wpwe	Weight of physical working environment in C&D waste management
WVjo	Weighted value of provision of job opportunities
WVlh	Weighted value of practitioners' long-term health
WVpimw	Weighted value of practitioners' initiative to minimize C&D waste
Subsystem of effectiveness of C&D waste management	
Ewm	Effectiveness of C&D waste management
W	Weight
Wecpv	Weight of economic performance value
Wenpv	Weight of environmental performance value
Wsopv	Weight of social performance value

Appendix B: Equations of the dynamic model

Subsystem of 'C&D Waste Generation'

AAWR(t) = AAWR(t - dt) + (RW) * dt

INIT AAWR = 0

RW = 124.29*WRR

ALLWT(t) = ALLWT(t - dt) + (ALWT) * dt

INIT ALLWT = 0

ALWT = IF SALWT<ELALWT and ALLWT<100 THEN 1.5 ELSE 0

AWMCwO(t) = AWMCwO(t - dt) + (CWMCwO) * dt

INIT AWMCwO = 0

CWMCwO = IF AWMCwO<=20 and WMCwO<= 10 THEN 4 ELSE IF AWMCwO<=40 THEN 3 ELSE IF AWMCwO<=60 THEN 1 ELSE 0

FDCs(t) = FDCs(t - dt) + (- DDCs) * dt

INIT FDCs = 70

DDCs = GRAPH(EMfWRD)

(0.00, 0.00), (10.0, 0.55), (20.0, 1.05), (30.0, 1.50), (40.0, 1.98), (50.0, 2.50), (60.0, 3.03), (70.0, 3.53), (80.0, 4.08), (90.0, 4.60), (100, 5.00)

ITCCB(t) = ITCCB(t - dt) + (CTCCB) * dt

INIT ITCCB = 0

CTCCB = IVTWM

IWM(t) = IWM(t - dt) + (CIWM) * dt

INIT IWM = 0

CIWM = AIIWM

IWRAS(t) = IWRAS(t - dt) + (IVTWM) * dt

INIT IWRAS = 0

IVTWM = GRAPH(ECWR)

(0.00, 0.00), (10.0, 0.345), (20.0, 0.6), (30.0, 0.885), (40.0, 1.19), (50.0, 1.48), (60.0, 1.75), (70.0, 2.02), (80.0, 2.36), (90.0, 2.70), (100, 3.00)

MCWR(t) = MCWR(t - dt) + (GEMW) * dt

INIT MCWR = 10

GEMW = IF MCWR<=60 and ECWR<=60 THEN 2 ELSE 1

PWtRW(t) = PWtRW(t - dt) + (CPWtRW) * dt

INIT PWtRW = 0

CPWtRW = IF PWtRW<EIRPWtRW THEN MEAN(IWRAS, PWE, MIMW) ELSE 1

WG(t) = WG(t - dt) + (WGR - RW) * dt

INIT WG = 0

WGR = CFAM*WGFA

RW = 124.29*WRR

AIIWM = IF EtRW<-50 THEN 3 ELSE IF EtRW<0 THEN 2 ELSE IF EtRW<60 THEN 1 ELSE 0

CFAM = 46999.5/18

CIWR = MEAN(PWRLC, IWRC)

EIRPWtRW = 60

ELALWT = 40

EMfWRD = 15

EtRW = IF (IALWT+IWMCwO+IDCs+IIWM+IMCWR+ISSL+CIWR)<-100 THEN -100 ELSE IF (IALWT+IWMCwO+IDCs+IIWM+IMCWR+ISSL+CIWR)>100 THEN 100 ELSE IALWT+IWMCwO+IDCs+IIWM+IMCWR+ISSL+CIWR

WGFA = 47.6/1000

WGM = IF (WGR-RW)>0 THEN (WGR-RW) ELSE 0

WMCwO = MEAN(ITCCB+ECWR+IPWtRW)

IALWT = GRAPH(ALLWT)

(0.00, -40.0), (10.0, -25.0), (20.0, -9.00), (30.0, -1.00), (40.0, 7.00), (50.0, 13.0), (60.0, 20.0), (70.0, 35.0), (80.0, 50.0), (90.0, 74.0), (100, 100)

IDCs = GRAPH(FDCs)

(0.00, -0.5), (10.0, -4.00), (20.0, -8.75), (30.0, -12.8), (40.0, -16.3), (50.0, -20.5), (60.0, -24.8), (70.0, -29.8), (80.0, -34.0), (90.0, -37.3), (100, -40.3)

IIWM = GRAPH(IWM)

(0.00, 0.00), (10.0, 3.00), (20.0, 7.00), (30.0, 10.5), (40.0, 14.0), (50.0, 18.5), (60.0, 22.5), (70.0, 27.0), (80.0, 32.0), (90.0, 38.5), (100, 45.0)

IMCWR = GRAPH(MCWR)

(0.00, 0.005), (10.0, 5.00), (20.0, 9.50), (30.0, 14.5), (40.0, 18.5), (50.0, 23.5), (60.0, 28.0), (70.0, 33.0), (80.0, 38.0), (90.0, 43.5), (100, 50.0)

IPWtRW = GRAPH(PWtRW)

(0.00, -40.0), (10.0, -33.0), (20.0, -24.0), (30.0, -15.0), (40.0, -4.00), (50.0, 6.00), (60.0, 19.0), (70.0, 37.0), (80.0, 49.0), (90.0, 57.0), (100, 60.0)

ISSL = GRAPH(SSL)

(0.00, 16.0), (10.0, 10.0), (20.0, 2.50), (30.0, -5.00), (40.0, -11.5), (50.0, -19.0), (60.0, -25.5), (70.0, -31.0), (80.0, -35.5), (90.0, -41.0), (100, -45.5)

IWMCwO = GRAPH(AWMCwO)

(0.00, -40.0), (10.0, -28.0), (20.0, -19.0), (30.0, -13.0), (40.0, -4.00), (50.0, 4.00), (60.0, 10.0), (70.0, 17.0), (80.0, 25.0), (90.0, 33.0), (100, 40.0)

IWRC = GRAPH(EcPV)

(-100, -44.0), (-80.0, -44.0), (-60.0, -44.0), (-40.0, -44.0), (-20.0, -39.0), (0.00, -35.0), (20.0, -29.0), (40.0, -22.0), (60.0, -17.0), (80.0, -10.0), (100, 0.00)

PWRLC = GRAPH(ULC)

(0.00, 0.00), (10.0, 16.5), (20.0, 29.0), (30.0, 36.0), (40.0, 41.0), (50.0, 45.0), (60.0, 49.0), (70.0, 51.5), (80.0, 55.5), (90.0, 63.5), (100, 77.0), (110, 88.0), (120, 92.5)

SALWT = GRAPH(ITCCB)

(0.00, 0.03), (10.0, 1.90), (20.0, 3.40), (30.0, 5.00), (40.0, 6.50), (50.0, 8.30), (60.0, 9.80), (70.0, 11.3), (80.0, 13.1), (90.0, 14.6), (100, 16.5)

SSL = GRAPH(TIME)

(1.00, 0.00), (2.00, 5.00), (3.00, 10.0), (4.00, 25.0), (5.00, 30.0), (6.00, 30.0), (7.00, 30.0), (8.00, 30.0), (9.00, 40.0), (10.0, 40.0), (11.0, 40.0), (12.0, 40.0), (13.0, 40.0), (14.0, 40.0), (15.0, 40.0), (16.0, 35.0), (17.0, 30.0), (18.0, 20.0)

WRR = GRAPH(EtRW)

(-100, 0.00), (-80.0, 0.05), (-60.0, 0.12), (-40.0, 0.16), (-20.0, 0.21), (0.00, 0.26), (20.0, 0.34), (40.0, 0.41), (60.0, 0.52), (80.0, 0.66), (100, 0.8)

Subsystem of 'Economic performance'

ACoW(t) = ACoW(t - dt) + (CoW - SW - IDW) * dt

INIT ACoW = 0

CoW = PWCo*WGM

SW = ACoW*PWS

IDW = ACoW*PIWD

AIDW(t) = AIDW(t - dt) + (IDW) * dt

INIT AIDW = 0

IDW = ACoW*PIWD

ARecW(t) = ARecW(t - dt) + (RecW) * dt

INIT ARecW = 0

RecW = ASW*PWRec

AReuW(t) = AReuW(t - dt) + (ReuW) * dt

INIT AReuW = 0

ReuW = ASW*PWReu

ASW(t) = ASW(t - dt) + (SW - ReuW - RecW - TWfStL) * dt

INIT ASW = 0

SW = ACoW*PWS

ReuW = ASW*PWReu

RecW = ASW*PWRec

TWfStL = ASW*PWDL

CWCo(t) = CWCo(t - dt) + (CWCoM) * dt

INIT CWCo = 0

CWCoM = CoW*UCWCo

CWDL(t) = CWDL(t - dt) + (CWDLM) * dt

INIT CWDL = 0

CWDLM = ULC*WDLM

CWS(t) = CWS(t - dt) + (CWSM) * dt

INIT CWS = 0

CWSM = SW*UCWS

PIWD(t) = PIWD(t - dt) + (IRIWD - DRIWD) * dt

INIT PIWD = 0.4

IRIWD = GRAPH(ULC)

(0.00, 0.0165), (12.0, 0.019), (24.0, 0.022), (36.0, 0.027), (48.0, 0.0315), (60.0, 0.0455), (72.0, 0.068), (84.0, 0.082), (96.0, 0.0885), (108, 0.096), (120, 0.1)

DRIWD = GRAPH(MIMW)

(0.00, 0.00), (10.0, 0.006), (20.0, 0.011), (30.0, 0.019), (40.0, 0.03), (50.0, 0.043), (60.0, 0.061), (70.0, 0.077), (80.0, 0.1), (90.0, 0.137), (100, 0.2)

R(t) = R(t - dt) + (RC) * dt

INIT R = 10

RC = IF PIWD>=0.30 and R<=50 THEN 2 ELSE 1

```
WDL(t) = WDL(t - dt) + (TWfStL) * dt

INIT WDL = 0

TWfStL = ASW*PWDL

A&CRF = 30

AUPNM = 360

CHIDW = UPID*AIDW

CWRec = ARecW*UCRec

CWReu = AReuW*UCWReu

CWTfStL = WDL*TDfStL*UCTfStL

EcPV = IF TIME=1 THEN 0 ELSE IF NPWM>=NPWMmax THEN 100 ELSE IF NPWM>=NPWMs and NPWM<NPWMmax THEN ((NPWM-NPWMs)/NPWMmax-NPWMs)*40+60 ELSE IF NPWM>=NPWMt and NPWM<NPWMs THEN 60*(NPWM-NPWMt)/(NPWMs-NPWMt) ELSE -100

MSvRec = ARecW

MSvReu = AReuW

NPWM = TBWM-TCWM

NPWMmax = 50000

NPWMs = 0

NPWMt = -10000

PWDL = 1-PWRec-PWReu

PWRec = (0.6*ILCR+0.4*A&CRF)/100
```

PWReu = 0.28

PWS = 1-PIWD

RSWM = AUPNM*TAMS

SCDRRM = TAMS*ULC

SCPRRM = TAMS*UCPM

SCTRRM = TAMS*UCTfStL

TAMS = MSvRec+MSvReu

TBWM = RSWM+SCDRRM+SCPRRM+SCTRRM

TCWM = CHIDW+CWCo+CWRec+CWReu+CWS+CWTfStL+CWDL

TDfStL = 16

UCPM = 60

UCRec = 20

UCTfStL = 2.5

UCWCo = 15

UCWReu = 15

UCWS = 15

ULC = 5.88

UPID = 60

WDLM = TWfStL+WGM*(1-PWCo)

ECWR = GRAPH(R)

(0.00, 0.00), (10.0, 13.0), (20.0, 24.0), (30.0, 35.0), (40.0, 44.5), (50.0, 51.5), (60.0, 57.5), (70.0, 64.0), (80.0, 68.5), (90.0, 71.0), (100, 73.0)

ILCR = GRAPH(ULC)

(0.00, 0.00), (12.0, 2.50), (24.0, 4.00), (36.0, 6.00), (48.0, 8.50), (60.0, 12.5), (72.0, 16.5), (84.0, 27.5), (96.0, 38.5), (108, 55.0), (120, 70.0)

MIMW = GRAPH(ECWR)

(0.00, 0.00), (10.0, 10.0), (20.0, 19.5), (30.0, 30.5), (40.0, 40.0), (50.0, 50.5), (60.0, 60.5), (70.0, 70.5), (80.0, 80.5), (90.0, 90.5), (100, 100)

PWCo = GRAPH(MIMW)

(0.00, 0.42), (10.0, 0.455), (20.0, 0.49), (30.0, 0.54), (40.0, 0.595), (50.0, 0.65), (60.0, 0.7), (70.0, 0.755), (80.0, 0.83), (90.0, 0.935), (100, 1.00)

Subsystem of 'Environmental Performance'

AAPPV(t) = AAPPV(t - dt) + (APPVM) * dt

INIT AAPPV = 0

APPVM = APPV/18

AEIID(t) = AEIID(t - dt) + (EIID) * dt

INIT AEIID = 0

EIID = IDW*MIDW

ANEPV(t) = ANEPV(t - dt) + (NEPVM) * dt

INIT ANEPV = 0

NEPVM = NEPV/18

LAO(t) = LAO(t - dt) + (WEL + TIDWtL) * dt

INIT LAO = 0

WEL = MWDL*TWfStL

TIDWtL = IDW*MWDL

WQ(t) = WQ(t - dt) + (- WQC) * dt

INIT WQ = 100

WQC = STEP(0, 0)+STEP(1, 2)+STEP(1.5, 5)

AP = SUM(IAPfStL, IAPRec, IIWD, MIWReu*ReuW)

APmin = 15

APPV = IF AP<=APmin THEN 100 ELSE IF AP<=APs and AP>APmin THEN ((AP-APs)/(APmin-APs))*40+60 ELSE IF AP<=APt and AP>APs THEN 60*(AP-APt)/(APs-APt) ELSE -100

APs = 65

APt = 80

EnPV = WVAP+WVEIID+WILC+WVNE+WVWQ

IAPfStL = MIAPfStL*TWfStL

IAPRec = MIAPRec*RecW

INECo = CoW*MINECo

INETfStL = MINETfStL*TWfStL

MIAPfStL = 0.5

MIAPRec = 0.5

MIDW = 0.02

MINECo = 0.5

MINETfStL = 0.5

MIWReu = 0.5

MWDL = 0.0667

NE = INECo+INETfStL

NEmin = 30

NEPV = IF NE<=NEmin THEN 100 ELSE IF NE<=NEs and NE>NEmin THEN ((NE-NEs)/(NEmin-NEs))*40+60 ELSE IF NE<=NEt and NE>NEs THEN 60*(NE-NEt)/(NEs-NEt) ELSE -100

NEs = 65

NEt = 80

Wap = 0.2

Weiid = 0.2

WILC = ((ILC-100)/(0-100)*100-100)*Wlao

Wiwp = 0.2

Wlao = 0.2

Wne = 0.2

WVAP = (APPV-100)*Wap

WVEIID = ((AEIID-100)/(0-100)*100-100)*Weiid

WVNE = (NEPV-100)*Wne

WVWQ = -((WQ-100)/(0-100))*100*Wiwp

IIWD = GRAPH(IDW)

(0.00, 0.00), (10.0, 12.0), (20.0, 24.5), (30.0, 34.5), (40.0, 43.0), (50.0, 51.0), (60.0, 56.0), (70.0, 63.0), (80.0, 74.0), (90.0, 88.5), (100, 100)

ILC = GRAPH(LAO)

(0.00, 0.00), (40.0, 7.50), (80.0, 15.0), (120, 22.5), (160, 30.5), (200, 39.5), (240, 49.5), (280, 59.5), (320, 69.5), (360, 82.5), (400, 100)

AERIWD(t) = AERIWD(t - dt) + (RIWD) * dt

INIT AERIWD = 0

RIWD = GRAPH(PARIWD)

(0.00, 1.50), (10.0, 1.58), (20.0, 1.68), (30.0, 1.88), (40.0, 2.10), (50.0, 2.43), (60.0, 2.73), (70.0, 3.10), (80.0, 3.45), (90.0, 4.05), (100, 5.00)

Subsystem of 'Social Performance'

AERIWDSI(t) = AERIWDSI(t - dt) + (IIDSI) * dt

INIT AERIWDSI = 0

IIDSI = GRAPH(AERIWD)

(0.00, 5.00), (10.0, 3.95), (20.0, 3.18), (30.0, 2.48), (40.0, 2.00), (50.0, 1.63), (60.0, 1.35), (70.0, 1.00), (80.0, 0.675), (90.0, 0.325), (100, 0.00)

AIPWE(t) = AIPWE(t - dt) + (CPWE) * dt

INIT AIPWE = 80

CPWE = GRAPH(PWE)

(0.00, -2.00), (10.0, -2.00), (20.0, -2.00), (30.0, -2.00), (40.0, -2.00), (50.0, -2.00), (60.0, -1.00), (70.0, -1.00), (80.0, 0.00), (90.0, 0.00), (100, 0.00)

LH(t) = LH(t - dt) + (ILH) * dt

INIT LH = 100

ILH = IF SoPV<=0 THEN -1 ELSE IF SoPV<=20 and Month<=12 THEN -2.5 ELSE -1.5

OS2(t) = OS2(t - dt) + (CSO) * dt

INIT OS2 = 100

CSO = GRAPH(OS)

(0.00, -2.00), (10.0, -2.00), (20.0, -2.00), (30.0, -2.00), (40.0, -2.00), (50.0, -2.00), (60.0, -1.00), (70.0, -1.00), (80.0, 0.00), (90.0, 0.00), (100, 0.00)

PIMW(t) = PIMW(t - dt) + (CPIMW) * dt

INIT PIMW = 0

CPIMW = IF APIMW<EPIMW THEN 2 ELSE IF PIMW>80 THEN 0 ELSE 1

EMaxJO = 20

EMinJO = 4

EPIMW = 60

Month = Time

OSs = 60

OSt = 30

PARIWD = IF IDW/WGM>=0.8 THEN 90 ELSE IF 0.6<=IDW/WGM<0.8 THEN 70 ELSE IF 0.4<=IDW/WGM<0.6 THEN 50 ELSE IF 0.2<=IDW/WGM<0.4 THEN 30 ELSE 15

PS = MEAN(60-AEIID, 60-AAPPV, 60-ANEPV, OS2-60, VJO-60)

SoPV = WPVridsi+WVlh+WPVos+WPVpariwd+WPVps+WPVpwe+WVjo+WVpimw

VJO = IF AJO>=EMinJO and AJO<=EMaxJO THEN (AJO-EMinJO)/(EMaxJO-EMinJO)*100 ELSE IF AJO>EMaxJO THEN 100 ELSE IF AJO<EMinJO THEN -100 ELSE 0

Wjo = 1/8

Wlh = 1/8

Wos = 1/8

Wpariwd = 1/8

Wpimw = 1/8

Wps = 1/8

WPVos = IF OS2>=100 THEN 0 ELSE IF OS2>=OSs and OS2<100 THEN (OS2-OSs)/(100-OSs)*40*Wos+60*Wos-100*Wos ELSE IF OS2>=OSt and OS2<OSs THEN 60*(OS2-OSt)/(OSs-OSt)*Wos-100*Wos ELSE -100*Wos

WPVpariwd = (PARIWD-100)/(0-100)*100*Wpariwd

WPVps = PS*Wps

WPVpwe = ((AIPWE-0)/(100-0)*100-100)*Wpwe

WPVridsi = PViidsi*Wridsi

Wpwe = 1/8

Wridsi = 1/8

WVjo = VJO*Wjo

WVlh = ((LH-0)/(100-0)*100-100)*Wlh

WVpimw = (PIMW-0)/(100-0)*100*Wpimw

AJO = GRAPH(TIME)

(1.00, 0.00), (2.00, 2.00), (3.00, 2.00), (4.00, 5.00), (5.00, 5.00), (6.00, 8.00), (7.00, 8.00), (8.00, 13.0), (9.00, 13.0), (10.0, 15.0), (11.0, 15.0), (12.0, 15.0), (13.0, 23.0), (14.0, 23.0), (15.0, 23.0), (16.0, 23.0), (17.0, 16.0), (18.0, 16.0)

APIMW = GRAPH(PWtRW)

(0.00, 0.00), (10.0, 5.50), (20.0, 11.5), (30.0, 18.5), (40.0, 24.0), (50.0, 33.0), (60.0, 42.5), (70.0, 52.0), (80.0, 63.0), (90.0, 79.5), (100, 100)

OS = GRAPH(SoPV)

(-100, 0.00), (-80.0, 9.50), (-60.0, 18.0), (-40.0, 25.5), (-20.0, 32.5), (0.00, 39.0), (20.0, 44.0), (40.0, 51.0), (60.0, 60.5), (80.0, 70.0), (100, 80.0)

PViidsi = GRAPH(AERIWDSI)

(0.00, 0.5), (10.0, 7.00), (20.0, 16.5), (30.0, 27.0), (40.0, 36.5), (50.0, 46.0), (60.0, 56.5), (70.0, 66.5), (80.0, 77.5), (90.0, 87.5), (100, 96.0)

PWE = GRAPH(SoPV)

(-100, 0.00), (-80.0, 9.50), (-60.0, 18.0), (-40.0, 25.0), (-20.0, 29.0), (0.00, 34.0), (20.0, 39.0), (40.0, 44.5), (60.0, 54.0), (80.0, 64.5), (100, 80.0)

Subsystem of 'Effectiveness of C&D Waste Management'

Ewm = EcPV*Wecpv+EnPV*Wenpv+SoPV*Wsopv

W = 1

Wecpv = 1/3

Wenpv = 1/3

Wsopv = W-Wecpv-Wenpv

REFERENCES

ABS (Australia Bureau of Statistics). (2007). *Australia's Environment: Issues and Trends*. 2007. http://www.abs.gov.au/.

Baldwin, A.N., Austin, S.A., Poon, C.S., Shen, L.Y., Wong, I. (2007). Reducing waste in high-rise residential buildings by information modeling at the design stage. *Surveying & Built Environment*, 18(1), 51-62.

Baldwin, A.N., Shen, L.Y., Poon, C.S., Austin, S.A., Wong, I. (2008). Modeling design information to evaluate pre-fabricated and pre-cast design solution for reducing construction waste in high rise residential buildings. *Automation in Construction*, 17(3), 333-341.

Begum, R.A., Siwar, C., Pereira, J.J., Jaafar, A.H. (2006). A benefit-cost analysis on the economic feasibility of construction waste minimization. *Resources, Conservation and Recycling*, 48(1), 86-98.

Begum, R.A., Siwar, C., Pereira, J.J., Jaafar, A.H. (2007a). Factors and values of willingness to pay for improved construction waste management – A perspective of Malaysia contractors. *Waste Management*, 27(12), 1902-1909.

Begum, R.A., Siwar, C., Pereira, J.J., Jaafar, A.H. (2007b). Implementation of waste management and minimization in the construction industry in Malaysia. *Resources, Conservation and Recycling*, 51(1), 190-202.

Begum, R.A., Siwar, C., Pereira, J.J., Jaafar, A.H. (2009). Attitude and behavioral factors in waste management in the construction industry of Malaysia. *Resources, Conservation and Recycling*, 53(6), 321-328.

Bell, N. (1998). *Waste Minimization and Resource Recovery*. The Environmental Design Guide, Gen 21, Vol. 2. Royal Australian Institute of Architects, Canberra.

Bianchini, G., Marrocchino, E., Tassinari, R., Vaccaro, C. (2005). Recycling of construction and demolition waste materials: a chemical-mineralogical appraisal. *Waste Management*, 25(2), 149-159.

Birgisdottir, H. (2004). Life cycle assessment of MSWI residues: recycling in road construction and landfilling. In: *Integrated Waste Management and Life Cycle Assessment Workshop and Conference*, Prague, Czech Republic.

Bossink, A.G., Brouwers, H.J.H. (1996). Construction waste: quantification and source evaluation. *Journal of Construction Engineering and Management*, 122(1), 55-60.

Chen, Z., Li, H., Wong, C.T.C. (2002). An application of bar-code system for reducing construction wastes. *Automation in Construction*, 11(5), 521-533.

Chini, A., Balachandran, S. (2002). Anticipating and responding to deconstruction through building design. In: *A. Chini and F. Schultmann (Eds.) Proceedings of the CIB Task Group 39 – Deconstruction Meeting*.

Germany.

Chini, A., Bruening, S. (2005). Deconstruction and materials reuse in the United States. In: *A. Chini (Eds.): Deconstruction and Materials Reuse – An International Overview*, CIB Publication 300.

CIRC (Construction Industry Review Committee). (2001). *Construct for Excellence*. Report of the Construction Industry Review Committee, Hong Kong CIRC.

Clark, R.M. (1978). *Analysis of Urban Solid Waste Services: A Systems Approach*. Ann Arbor Science, Ann Arbor, Michigan, USA.

Clark, C., Jambeck, J., Townsend, T. (2006). A review of construction and demolition debris regulations in the United States. *Critical Reviews in Environmental Science and Technology*, 36(2), 141-186.

CMRA (Construction Materials Recycling Association). (2005). http://www.cdrecycling.org/.

Coyle, R.G. (1983). The technical elements of the system dynamics approach. *European Journal of Operational Research*, 14(4), 359-370.

Coyle, R.G. (1996). *System Dynamics Modeling: a Practical Approach*. London: Chapman & Hall.

Craven, D.J., Okraglik, H.M., Eilenberg, I.M. (1994) Construction waste and a new design methodology. In: *Kibert, C.J. (ed.), Sustainable Construction*. Center for Construction and Environment, Gainesville, FL, pp. 89-98.

Craighill, A., Powell, J.C. (1999). A lifecycle assessment and evaluation of construction and demolition waste. *CSERGE Working Paper WM 99-03*.

Dale, A., Chapman, P., McDonald, M. (1997). Social impact assessment in Queensland: why practice lags behind legislative opportunity. *Impact Assessment*, 15(2), 159-179.

DETR (Department of the Environment, Transport and the Regions). (2000). *Building a Better Quality of Life - A Strategy for More Sustainable Construction*. DETR, London.

DOE (Department of the Environment). (1994). *Guidelines for Aggregates Provision in England.* Minerals Planning Guidance Note 6. HMSO: London.

Dong, S.S., Tong, K.W., Wu, Y.P. (2001). Municipal solid waste management in China: using commercial management to solve a growing problem. *Utilities Policy*, 10, 7-11.

Dorsthorst, B., Kowalczyk, T. (2005). State of deconstruction in the Netherlands. In: *A. Chini (Eds.): Deconstruction and Materials Reuse – An International Overview*, CIB Publication 300.

Du Plessis, C. et al. (2002). *Agenda 21 for Sustainable Construction in Developing Countries*. CSIR Report BOU/E0204, CSIR, CIB and UNEP-IETC, Pretoria.

Duran, X., Lenihan, H., O'Regan, B. (2006). A model for assessing the economic viability of construction and demolition waste recycling – the case of Ireland. *Resources, Conservation and Recycling*, 46(3), 302-320.

Dyson, B., Chang, N.B. (2005). Forecasting municipal solid waste generation in a fast-growing urban region with system dynamics modeling. *Waste Management*, 25(7), 669-679.

Ekanayake, L.L., Ofori, G. (2004). Building waste assessment score: deign-based tool. *Building and Environment*, 39(7), 851-861.

Elias-Ozkan, S.T. (2005). The state of deconstruction in Turkey. In: *A. Chini (Eds.): Deconstruction and Materials Reuse – An International Overview*, CIB Publication 300.

Emmanuel, R. (2004). Estimating the environmental suitability of wall materials: preliminary results from Sri Lanka. *Building and Environment*, 39, 1253-1261.

Esin, T., Cosgun, N. (2007). A study conducted to reduce construction waste generation in Turkey. *Building and Environment*, 42(4), 1667-1674.

EWC (European Waste Catalogue). (2002). www.environment-agency.gov.uk.

Faniran, O.O., Caban, G. (1998). Minimizing waste on construction project sites. *Engineering, Construction and Architectural Management*, 5(2), 182-188.

Fatta, D., Papadopoulos, A., Avramikos, E., Sgourou, E., Moustakas, K., Kourmoussis, F., Mentzis, A., Loizidou, M. (2003). Generation and management of construction and demolition waste in Greece - an existing challenge. *Resources, Conservation and Recycling*, 40(1), 81-91.

Ferguson, J., Kermode, N., Nash, C.L., Sketch, W.A.J., Huxford, R.P. (1995). *Managing and Minimizing Construction Waste: A Practical Guide*. Institution of Civil Engineers, London.

Finnveden, G., Bjorklund, A., Moberg, A., Ekvall, T. (2007). Environmental and economic assessment methods for waste management decision-support: possibilities and limitation. *Waste Management and Research*, 25, 263-269.

Forrester, J.W. (1961). *Industrial Dynamics*. M.I.T. Press, Cambridge, Mass.

Forrest, J.W. (1994). System dynamics, system thinking and Soft OR. *System Dynamics Review*. 10(2), 245-256.

Forrester, J.W., Senge, P. (1980). Tests for building confidence in system dynamics models. In: *Legasto, A.A., Forrester, J.W. and Lyneis, J.M. (Eds.): System Dynamics: TIMS Studies in the Management Sciences.* 14, North-Holland, Amsterdam, 209-228.

Formoso, T.C., Soibelman M.L., De Cesare, C., Isatto, E.L. (2002). Material waste in building industry: main causes and prevention. *Journal of Construction Engineering and Management*, 128(4), 316-325.

Forsthe, P., Marsden, P.K. (1999). Modeling construction waste performance – an arising procurement issue. In: *S.O.Ogunlana, (ed.), Profitable Partnering in Construction Procurement, CIB TG23 (Culture in*

Construction) Joint Symposium, Spon, London, 679-688.

Gavilan, R.M., Bernold, L.E. (1994). Source evaluation of solid waste in building construction. *Journal of Construction Engineering and Management*, 120(3), 536-552.

Georgiadis, P., Vlachos, D. (2004). The effect of environmental parameters on product recovery. *European Journal of Operational Research*, 157(2), 449-464.

Graham, P.M., Smithers, G. (1996). Construction waste minimization for Australian residential development. *Asia Pacific Building and Construction Management Journal*, 2(1), 14-19.

Guneralp, B., Barlas, Y. (2003). Dynamic modeling of a shallow freshwater lake for ecological and economic sustainability. *Ecological Modeling*, 167(1), 115-138.

Guthrie, P., Woolveridge, A.C., Patel, V.S. (1999). *Waste Minimization in Construction: Site Guide*. London: Construction Industry Research and Information Association.

Hadjieva-Zaharieva, R., Dimitrova, E., Buyle-Bodin, F. (2003). Building waste management in Bulgaria: challenges and opportunities. *Waste Management*, 23(8), 749-761.

Hao, J.L., Yuan, H.P., Wang, J.Y., Tam, V.W.Y., Hills, M.J. (2007a). Construction waste challenges in Hong Kong and the Pearl River Delta Region. In: *CRIOCM 2007 International Research Symposium on*

Advancement of Construction Management and Real Estate, pp. 831-840.

Hao, J.L., Hills, M.J., Huang, T. (2007b). A simulation model using system dynamic method for construction and demolition waste management in Hong Kong. *Journal of Construction Innovation*, 7(1), 7-21.

Hao, J.L., Hills, M.J., Tam, V.W.Y. (2008a). The effectiveness of Hong Kong's Construction Waste Disposal Charging Scheme. *Waste Management & Research*, 26(6), 553-558.

Hao, J.L., Hills, M.J., Shen, L.Y. (2008b). Managing construction waste on-site through system dynamics modeling: the case of Hong Kong. *Engineering, Construction and Architectural Management*, 15(2), 103-113.

Hao, J.L., Tam. V.W.Y., Yuan, H.P., Wang, J.Y., Li, J.R. (2010). Dynamic modeling of construction and demolition waste management processes: an empirical study in Shenzhen, China. *Engineering, Construction and Architectural Management*, 17(5), 476-492.

Hendriks, C.F., Pietersen, H.S. (2000). *Sustainable Raw Materials: Construction and Demolition Waste*. RILEM Publication, Cachan Cedex, France.

High Performance Systems Inc. (2006). *An Introduction to System Thinking. "iThink" Users Manual.* High Performance Systems Inc.

HKEPD (Hong Kong Environment Protection Department). (2006).

Monitoring of Solid Waste in Hong Kong. https://www.wastereduction.gov.hk/en/materials /info/.

HKEPD (Hong Kong Environment Protection Department). (2007). *Monitoring of Solid Waste in Hong Kong*. https://www.wastereduction.gov.hk/en/materials/ info/.

HK (Hong Kong) Government. (2006). http://www.info.gov.hk.

Howard Humphreys and Partners. (1994). *Managing Demolition and Construction Wastes: Report of the study on the Recycling of Demolition and Construction Wastes in the UK*. Report for the Department of the Environment. HMSO: London.

Hurley, J., Hobbs, G. (2005). UK country report on deconstruction. In: *A. Chini (Eds.): Deconstruction and Materials Reuse – An International Overview*, CIB Publication 300.

IAIA (International Association of Impact Assessment). (2011). http://www.iaia.org/.

Innes, S. (2004). Developing tools for designing out waste pre-site and on-site. In: *Proceedings of Minimising Construction Waste Conference: Developing Resource Efficiency and Waste Minimisation in Design and Construction*. New Civil Engineer, London.

Inyang, H.I. (2003). Framework for recycling of wastes in construction. *Journal of Environmental Engineering*, 129(10), 887-898.

ISO (International Organization for Standardization). (2006). *International*

Standard ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework. Geneva, Switzerland.

Jaillon, L., Poon, C.S. (2008). Sustainable construction aspects of using prefabrication in dense urban environment: a Hong Kong case study. *Construction Management and Economics*, 26(9), 953-966.

Jaillon, L., Poon, C.S., Chiang, Y.H. (2009). Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Management*, 29(1), 309-320.

Kang, X.P. (2005). *The Research of Reducing Methods of Construction Waste*. Master thesis of Shenzhen University, China.

Karavezyris, V. (2007). Treatment of commercial, construction and demolition waste in North Rthine-Westphalia: policy-making and operation options. *Waste Management*, 25(2), 183-189.

Kauffman, D.L. (1981). *System One: An Introduction to Systems Thinking*. 2nd edition. Future Systems Inc., Minneapolis.

Kartam, N., Al-Mutairi, N., Al-Ghusain, I., Al-Humoud, J. (2004). Environmental management of construction and demolition waste in Kuwait. *Waste Management*, 24(10), 1049-1059.

Kellet, J.E. (1995). The elements of a sustainable aggregates policy. *Journal of Environmental Planning and Management,* 38 (4), 569-579.

Kibert, C., Chini, A., Languell, J. (2000). Implementing deconstruction in the United States. In: *C. Kibert and A. Chini (Eds.): Overview of*

Deconstruction in Selected Countries, CIB Publication 252.

Kirkwood, C.W. (1998). *System Dynamics Methods: A Quick Introduction*. Department of Management, Arizona State University; USA.

Klang, A., Vikman, P., Brattebo, H. (2003). Sustainable management of demolition waste - an integrated model for the evaluation of environmental, economic and social aspects. *Resources, Conservation and Recycling*, 38, 317-334.

Kofoworola, O.F., Gheewala, S.H. (2009). Estimation of construction waste generation and management in Thailand. *Waste Management*, 29(2), 731-738.

Kulatunga U., Amaratunga D., Haigh R., Rameezdeen, R. (2006). Attitudes and perceptions of construction workforce on construction waste in Sri Lanka. *Management of Environmental Quality: An International Journal*, 17(1), 57-72.

Lam, A.L.P. (1997). *A Study of the Development of Environmental Management in Hong Kong Construction Industry*. BSc Thesis, The Hong Kong Polytechnic University.

Lauritzen, E.K. (1998). Emergency construction waste management. *Safety Science*, 30(1-2), 45-53.

Leigh, N.G., Patterson, L.M. (2005). *Construction and Demolition Debris Recycling for Environmental Protection and Economic Development*. Southeast Regional Environmental Finance Center, USA.

Li, H., Chen, Z., Yong, S.C.W.K. (2005). Application of integrated GPS and GIS technology for reducing waste and improving construction efficiency. *Automation in Construction*, 14(3), 323-331.

Li, J.F., Zhang, G.S., Liu, F.C. (2001). The environmental impact of urban construction rubbish and countermeasures. *Journal of Anhui Normal University (Natural Science)*, 24(4), 336-342.

Li, N.Z., Wang, B.Q., Zhang, L.X., Song, J. (1999). The techniques for C&D waste reuse. *Environment Protection*, 10, 43-44.

Li, P. (2006). *Integrated Utilization of C&D Waste to Develop Circle Economy*. Review report by the Shenzhen Construction Bureau.

Lin Z.W. (2006). *Model Development for estimating the quantity of A Single Building's Demolition Waste*. National Central University.

Lin, J., Chai, K.H., Wong, Y.S., Brombacher, A.C. (2008). A dynamic model for managing overlapped iterative product development. *European Journal of Operational Research*, 185(1), 378-392.

Ling, Y.Y., Leo, K.C. (2000). Reusing timber formwork: importance of workmen's efficiency and attitude. *Building and Environment*, 35(2), 135-143.

Lingard, H., Graham, P., Smithers, G. (2000). Employee perceptions of the solid waste management system operation in a large Australia contracting organization: implications for company policy implementation. *Construction Management and Economics*, 18(4), 383-393.

Lu, M., Poon, C.S., Wong, L.C. (2006). Application framework for mapping and simulation of waste handling processes in construction. *Journal of Construction Engineering and Management*, 132(11), 1212-1221.

Lu, W.S., Yuan, H.P. (2010). Exploring critical success factors for waste management in construction projects of China. *Resources, Conservation and Recycling*, 55(2), 201-208.

Lu, W.S., Yuan, H.P. (2011). A framework for understanding waste management studies in construction. *Waste Management*, 31(6), 1252-1260.

Lu, W.S., Yuan, H.P., Li, J.R., Hao, J.L., Mi, X.M., Ding, Z.K. (2010). An empirical investigation of construction and demolition waste generation rates in Shenzhen city, South China. *Waste Managemen*t, 31, 680-687.

Maani, K.E., Cavana, R.Y. (2000). *System Thinking and Modeling – Understanding Change and Complexity*. Prentice Hall, Auckland.

Maani, K.E., Mahara, J. (2004). Links between systems thinking and complex decision making, *System Dynamics Review*. 20(1), 21-48.

Macozoma, D.S. (2001). Building deconstruction. In: *D. Macozoma (Eds.) CIB Gy. Sebesystem Fellowship 2001: Construction Waste*. CIB Publication 278.

McDonald, B., Smithers, M. (1998). Implementing a waste management plan during the construction phase of project: a case study. *Construction*

Management and Economics, 16(1), 71-78.

McGrath, C. (2001). Waste minimization in practice. *Resource, Conservation and Recycling*, 32(3-4), 227-238.

McGrath, C., Anderson, M. (2000). *Waste Minimizing on a Construction Site*. Building Research Establishment Digest No. 447.

McGregor, M, Washburn, H., Palermini, D. (1993). *Characterization of Construction Site Waste: Final Report*. Presented to the METRO solid waste department, Portland, Oregon.

Mills, T.H., Showalter, E., Jarman, D. (1999). A cost effective waste management plan. *Cost Engineering*, 41(3), 35-43.

Morris Specifications Inc. (2001). *Construction Waste Management and Disposal: Model Specification*. Metro Vancouver Waste Management Master Specification.

NAHB Research Center. (2001). *Materials Salvaged Through Deconstruction: A Case Study of Riverdale Village Apartments*. http://www.epa.gov/osw/ conserve/rrr/imr/cdm/pubs/decon_br.pdf.

NBS (National Bureau of Statistics of China). (2007). *Shanghai Statistical Yearbook*. Beijing: Beijing Statistics Press.

NBS (National Bureau of Statistics of China). (2009). *Shenzhen Statistical Yearbook*. Beijing: Beijing Statistics Press.

Nitivattananon, V., Borongan, G. (2007). Construction and demolition waste management: current practices in Asia. In: *Proceedings of the*

International Conference on Sustainable Solid Waste Management, Chennai, India. pp. 97-104.

Nunes, K.R.A., Mahler, C.F., Valle, R., Neves, C. (2007). Evaluation of investments in recycling centers for construction and demolition wastes in Brazilian municipalities. *Waste Management*, 27(11), 1531-1540.

Oberstainer, G., Binner, E., Mostbauser, P., Salhofer, S. (2007). Land modeling in LCA - a contribution based on empirical data. *Waste Management*, 27, 58-74.

Ofori, G. (1992). The environment: the fourth construction project objective?. *Construction Management and Economics*, 10(5), 369-395.

Ortiz, O., Pasqualino, J.C., Castells, F. (2010). Environmental performance of construction waste: comparing three scenarios from a case study in Catalonia, Spain. *Waste Management*, 30(4), 646-654.

Osmani, M., Glass J., Price, A.D.F. (2006). Architect and contractor attitudes to waste minimization. In: *Proceedings of the Institution of Civil Engineers: Waste and Resource Management*, 159(No. WR2), pp. 65-72.

Osmani, M., Glass J., Price, A.D.F. (2008). Architects' perspectives on construction waste reduction by design. *Waste Management*, 28(7), 1147-1158.

Peng, C.L., Scorpio, D.E., Kitbert, C.J. (1997). Strategies for successful construction and demolition waste recycling operations. *Construction*

Management and Economics, 15(1), 49-58.

Petkovic, G., Engelsen, C.J., Haoya, A., Breedveld, G. (2004). Environmental impact form the use of recycled materials in road construction: method for decision-making in Norway. *Resources, Conservation and Recycling*, 42(3), 249-264.

Poon, C.S. (2007). Reducing construction waste. *Waste Management*, 27(12), 1715-1716.

Poon, C.S., Chan, D. (2007). The use of recycled aggregate in concrete in Hong Kong. *Resources, Conservation and Recycling*, 50(3), 293-305.

Poon, C.S., Yu, A.T.W., Ng, L.H. (2001a). *A Guide for Managing and Minimizing Building and Demolition Waste*. The Hong Kong Polytechnic University, Hong Kong.

Poon, C.S., Yu, A.T.W., Ng, L.H. (2001b). On-site sorting of construction and demolition waste in Hong Kong. *Resources, Conservation and Recycling*, 32(2), 157-172.

Poon, C.S., Yu, A.T.W., Ng, L.H. (2003). Comparison of low-waste building technologies adopted in public and private housing projects in Hong Kong. *Engineering, Construction and Architectural Management*, 10(2), 88-98.

Poon, C.S., Yu, A.T.W., Wong, S.W., Cheung, E. (2004a). Management of construction waste in public housing projects in Hong Kong. *Construction Management and Economics*, 22(7), 675-689.

Poon, C.S., Yu, A.T.W., Jaillon, L. (2004b). Reducing building waste at construction sites in Hong Kong. *Construction Management and Economics*, 22(5), 461-470.

Poon, C.S., Yu, A.T.W., See, S.C., Cheung, E. (2004c). Minimizing demolition wastes in Hong Kong public housing projects. *Construction Management and Economics*, 22(8), 799-805.

Qiu, D. (1991). *Systematic Analysis of Methods for Multi-indicator Assessment*. China Statistics Press, China.

Rao, A., Jha, K.N., Misra, S. (2007). Use of aggregate from recycled construction and demolition waste in concrete. *Resources, Conservation and Recycling*, 50(1), 71-81.

Reddrop, A., Ryan, C. (1997). *Housing Construction Waste*. Canberra: Commonwealth Department of Industry, Science and Tourism.

Richardson, G.P., Otto, P. (2008). Application of system dynamics in marketing: Editorial. *Journal of Business Research*, 61(11), 1099-1101.

Richardson, G.P., Pugh, A.L. (1989). *Introduction to System Dynamics Modeling*. Pegasus Communication, Waltham, Massachusetts.

Rocha, C.G., Sattler, M.A. (2009). A discussion on the reuse of building components in Brazil: an analysis of major social, economical and legal factors. *Waste Management*, 54, 104-112.

Roche, T.D., Hegarty, S. (2006). *Best Practice Guidelines on the Preparation of Waste Management Plans for Construction and Demolition Projects*.

http://www.envirocentre.ie/includes/documents/BPGConstructionand%20demolition.pdf.

Rodregues, A., Bowers, J. (1996). The role of system dynamics in project management. *International Journal of Project Management*, 14(4), 213-220.

Rogoff, M.J., Williams, J.F. (1994). *Approaches to Implementing Solid Waste Recycling Facilities*. Noyes, Park Ridge, NJ.

Sandler, K., Swingle, P., (2006). *OSWER Innovations Pilot: Building Deconstruction and Reuse*. http://www.epa.gov/oswer/.

Saunders, J., Wynn, P. (2004). Attitudes towards waste minimization amongst labor only sub-contractors. *Structural Survey*, 22(3), 148-155.

Saysel, A.K., Barlas, Y. (2001). A dynamic model of salinization on irrigated lands. *Ecological Modeling*, 139(2), 177-199.

Schultmann, F., Sunke, N. (2007). Organization of reverse logistics tasks in the construction industry. In: *I. Bragance et al. (Eds.): Sustainable Construction, Materials and Practices*, IOS Press.

Seadon, J.K. (2010). Sustainable waste management systems. *Journal of Cleaner Production*, 18(16-17), 1639-1651.

Sealey, B.J., Phillips, P.S., Hill, G.J. (2001). Waste management issues for the UK ready-mixed concrete industry. *Resources, Conservation and Recycling*, 32(3-4), 321–331.

Senge, P.M. (1990). *The Fifth Discipline: The Art and Practice of the*

Learning References Organization. Doubleday Currency, New York.

Serpell, A., Alarcon, L.F. (1998). Construction process improvement methodology for construction projects. *International Journal of Project Management*, 16(4), 215-221.

Seydel, A., Wilson, O.D., Skitmore, R.M. (2002). Financial evaluation of waste management methods: a case study. *Journal of Construction Research*, 3(1), 167-179.

SD Group (System Dynamics Group, Solan School of Management, MIT). (2009). What is system dynamics. http://scripts.mit.edu/~sdg/.

Shen, L.Y., Tam, V.W.Y. (2002). Implementation of environmental management in the Hong Kong construction industry. *International Journal of Project Management*, 20(7), 535-543.

Shen, L.Y., Tam, V.W.Y., Tam, C.M., Drew, D. (2004). Mapping approach for examining waste management on construction sites. *Journal of Construction Engineering and Management*, 130(4), 472-481.

Shen, L.Y., Wu, Y.Z., Chan, E.H.W., Hao, J.L. (2005). Application of system dynamics for assessment of sustainable performance of construction projects. *Journal of Zhejiang University*, 6A(4), 339-349.

Shen, L.Y., Yao, H., Alan, G. (2006). Improving environmental performance by means of empowerment of contractors. *Management of Environmental Quality: An International Journal*, 17(3), 242-257.

Shen, L.Y., Hao, J.L., Tam, V.W.Y., Yao, H. (2007). A checklist for assessing sustainable performance of construction projects. *Journal of Civil Engineering and Management*, 13(4), 273-281.

Shi, T., Gill, R. (2005). Developing effective policies for the sustainable development of ecological agriculture in China. *Ecological Modeling*, 53(2), 223-246.

Sjostrom, C., Bakens, W. (1999). CIB agenda 21 for sustainable construction. *Building Research & Information*, 27(6), 347-353.

Skoyles, E.R. (1976). Materials wastage - a misuse of resources. *Building Research and Practice* July/August, 232-243.

Skoyles, E.R., Skoyles, J.R. (1987). *Waste Prevention On Site*. London: Mitchell Publishing.

Skovgaard, M., Ibenholt, K., Ekvall, T. (2007). *Nordic Guideline for Cost-benefit in Waste Management*. Nordic Council of Ministers.

Snook, K., Turner, A., Ridout, R. (1995). *Recycling Waste from the Construction Site*. England: Chartered Institute of Building.

Stave, K.A. (2003). A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. *Journal of Environmental Management*, 67(4), 303-313.

Sterman, J.D. (1992). *System Dynamics Modeling for Project Management*. MIT, Cambridge, MA.

Sterman, J. D. (2000). *Business Dynamics System Thinking and Modeling for a Complex World*. McGraw-Hill, London.

Storey, J.B., Gjerde, M., Charleson, A., Pedersen, M. (2005). The state of deconstruction in New Zealand. In: *A. Chini (Eds.): Deconstruction and Materials Reuse – An International Overview*, CIB Publication 300.

Suarez, C.J., Malave, R.E. (2002). Characterization of aggregates from recycled C&D waste. In: *A. Chini and F. Schultmann (Eds.) Proceedings of the CIB Task Group 39 – Deconstruction Meeting*. Germany.

Symonds Group Ltd. (1999). *Construction and Demolition Waste Management Practices and Their Economic Impacts*. http://ec.europa.eu/environment /waste/studies/cdw/cdw_chapter1-6.pdf.

Tam, V.W.Y. (2008a). On the effectiveness in implementing a waste management plan method in construction. *Waste Management*, 28(6), 1072-1080.

Tam, V.W.Y. (2008b). Economic comparison of concrete recycling: a case study approach. *Resources, Conservation and Recycling*, 52(5), 821-828.

Tam, V.W.Y., Kotrayothar, D., Loo, Y.C. (2009). On the prevailing construction waste recycling practices: a South East Queensland study. *Waste Management and Research*, 27(2), 167-174.

Tam, V.W.Y., Shen, L.Y., Tam, C.M. (2007a). Assessing the levels of material wastage affected by sub-contracting relationships and projects types with their correlations. *Building and Environment*, 42(3), 1471-1477.

Tam, V.W.Y., Tam, C.M., Zeng, S.X., Ng, C.Y. (2007b). Towards adoption of prefabrication in construction. *Building and Environment*, 42(10), 3642-3654.

Tam, V.W.Y., Shen, L.Y., Fung, W.H., Wang, J.Y. (2007c). Controlling construction waste by implementing governmental ordinances in Hong Kong. *Journal of Construction Innovation*, 7(2), 149-166.

Tam, V.W.Y., Tam, C.M. (2006a). A review on the viable technology for construction waste recycling. *Resources, Conservation and Recycling*, 47(3), 209-221.

Tam, V.W.Y., Tam, C.M. (2006b). Evaluation of existing waste recycling methods: a Hong Kong study. *Building and Environment*, 41(12), 1649-1660.

Tam, V.W.Y., Tam, C.M. (2008). Waste reduction through incentives: a case study. *Building Research and Information*, 36(1), 37-43.

Tam, C.M., Tam, V.W.Y., Chan, J.K.W., Ng, W.C.Y. (2005). Use of prefabrication to minimize construction waste – a case study approach. *International Journal of Construction Management*, 5(1), 91-101.

Teo, M.M.M., Loosemore, M. (2001). A theory of waste behavior in the construction industry. *Construction Management and Economics*, 19(7), 741-751.

Trankler, J.O.V., Walker, I., Dohmann, M. (1996). Environmental impact of demolition waste—an overview on 10 years of research and experience. *Waste Management*, 16(1-3), 21-26.

Treloar, G.J., Gupta, H., Love, P.E.D., Nguyen, B. (2003). An analysis of factors influencing waste minimization and use of recycled materials for the construction of residential buildings. *Management of Environmental Quality: An International Journal*, 14(1), 134-145.

TuTech Innovation GmbH. (2004). *Strategy for Sustainable Construction and Demolition Waste Management in Galle, Sri Lanka*. http://www.cowam-project.org/cms/Content/download/Interim_Report_Vision_2018.pdf.

US EPA (Environmental Protection Agency). (2002). *Waste Wise Update: Building for the Future*. http://www.epa.gov/wastewise/pubs/wwupda16.pdf.

US EPA (Environmental Protection Agency). (2003). *Estimating 2003: Building-Related Construction and Demolition Materials Amounts*. http://www. epa.gov/osw/conserve/rrr/imr /cdm/pubs/cd-meas.pdf.

US Green Building Council. (2008). *LEED for New Construction*. http://www.usgbc.org/DisplayPage.aspx?CMSPageID=220.

Wang, J.Y., Kang X.P., Tam, V.W.Y. (2008). An investigation of construction wastes: an empirical study in Shenzhen. *Journal of Engineering, Design and Technology*, 6(3), 227-236.

Wang, J.Y., Touran, A., Christoforou, C., Fadlalla, H. (2004a). A system analysis tool for construction and demolition wastes management. *Waste Management*, 24(10), 987-997.

Wang, J.Y., Kang, X.P., Shen, L.Y., Tan, Y.E. (2004b). Research on management measures for reducing construction waste. *Architecture Technology*, 35(10), 732-734.

Wang, J.Y., Yuan, H.P. (2006). Integrated analysis of the current situation of construction industry in Chinese eight major provinces and cities. *Construction Economy*, 9, 5-8.

Wang, J.Y., Yuan, H.P. (2008). On-site construction waste management model based on system dynamics. *Science and Technology Progress and Policy*, 25(10), 74-78.

Wang, J.Y., Yuan, H.P., Kang, X.P., Lu, W.S. (2010). Critical success factors for on-site sorting of construction waste: a China study. *Resources, Conservation and Recycling*, 54, 931-936.

WCED (World Commission on Environment and Development). (1987). *Our Common Future*. UK: Oxford University Press. pp. 1-23.

Wikipedia. (2011). Environmental impact assessment. http://en.wikipedia.org/ wiki/Environmental_impact_assessment.

Winz, I., Brierley, G., Trowsdale, S. (2009). The use of system dynamics simulation in water resources management. *Waste Resources Management*, 23(7), 1301-1323.

Wolstenholme, E.F. (1990). *System Enquiry – A System Dynamics Approach*. John Wiley & Sons, Chichester.

Wolstenholme, E.F. (1997). System dynamics in the elevator (SD1163). E-mail communication: system-dynamics@world.std.com

Wolstenholme, E., Monk, D., McKelvie, D., Arnold, S. (2007). Coping but not coping in health and social care: masking the reality of running organizations beyond safe design capacity. *System Dynamics Review*, 23(4), 371-389.

WRAP. (2010). *Welsh Assembly Government: Interim Statement on Policy for Construction and Demolition Waste*. http://www.wrap.org.uk/construction/.

Yuan, H.P. (2008). *Construction and Demolition Waste Management Model Based on System Dynamics*. Master thesis of Shenzhen University, China.

Yuan, H.P., Shen, L.Y. (2011). Trend of the research on construction and demolition waste management. *Waste Management*, 31, 670-679.

Yuan, H.P., Shen, L.Y, Hao, J.L., Lu, W.S. (2010). A model for cost-benefit analysis of construction and demolition waste management throughout the waste chain. *Resources, Conservation and Recycling*, doi: 10.1016/j.resconrec.2010.06.004.

Yuan, H.P., Shen, L.Y., Wang, J.Y. (2011). Major obstacles to improving the performance of waste management in China's construction industry.

Facilities, 29(5/6), 224-242.

Zhang, X.F. (1995). Research on the reuse of construction waste. *Yangtse Construction*, 2, 24-26.

Zhu, T. (2009). *The Great Hall of the People in the Great Leap Forward*. Domus: China (Milan; Beijing: Siruius International), 37, 47-64.

Zygouras, M., Karagiannidis, A., Malamakis, A. (2009). Construction and demolition waste processing in Athens, Greece: a pilot demonstration. *International Journal of Environment and Waste Management*, 3(1/2), 177-192.