ENVIRONMENTAL MANAGEMENT IN CONSTRUCTION

A QUANTITATIVE APPROACH

Zhen Chen & Heng Li

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Foreword

The interconnectedness between resources consumption and the activities of individuals in environmental management is often appreciated in qualitative regulations, but sometimes it is not sufficiently recognized in quantitative studies. Too frequently the implications of how the interaction between all elements of an environmental management system influence the enterprise, project, or process is left only to descriptive prose. It is only recently that technologies have been developed which enable practitioners to assess potential environmental risks in construction management. These technologies now allow practitioners to conduct environmentally-oriented management with information systems which have knowledge bases embedded within them. This book presents a quantitative approach to environmental management based on an integration of an effective decision-making model with a knowledge re-use framework and a system for quantifying environmental impacts of construction activities for complex environmental management of construction projects. Case studies have been provided to illustrate to practical uses of the quantitative methods presented in the book.

The integrated approach to environmental management presented in this book is a very useful contribution to the development of environmental management systems. It suggests a helpful tool for both academics and practitioners to make progress in avoiding the mistakes of the past and to encourage the promotion of sustainable resource utilization in future construction project management.

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Director of the Salford University "Think Lab"
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Preface

Strategic environmental management under the ISO 14000 series of environmental management standards requires tactical approaches to support its implementation. For this reason, the authors developed a set of quantitative approaches to minimizing adverse environmental impacts in the construction industry. The primary aim of this book is to demonstrate how quantitative approaches can be made serviceable to environmental management in the construction industry. Specifically, the book illustrates how quantitative methods can be applied to measure the degree of adverse environmental impacts that are generated by construction activities onto the surrounding areas, and how to reduce such impacts through minimizing the wastage of materials and equipments, and maximizing the re-use, recycling, and recovery of construction wastes in the construction industry. In addition to the quantitative approaches, a knowledge-driven system for effective environmental management in construction is also presented.

The uniqueness of this book is reflected in three aspects. First, it has comprehensive coverage of literature related to the field of environmental management in construction. Second, it is the first book that presents an integrated system which can quantitatively control and manage adverse environmental impacts generated from construction activities. Third, it presents a knowledge-driven framework which can be conveniently implemented into a computer-based system to further support effective environmental management in construction.

This book is ideal as a textbook for both undergraduate and postgraduate students in construction engineering and management related fields.

Zhen Chen & Heng Li
2006

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List of abbreviations

A&I	Adoption and Implementation
AHP	Analytic Hierarchy Process
ANN	Artificial Neural Network
ANP	Analytic Network Process
C&D	Construction and Demolition
CM	Construction Management
CPI	Construction Pollution Index
EIA	Environmental Impact Assessment
EM	Environmental Management
EMS	Environmental Management System
EPA	External Patch Antenna
ERP	Enterprise Resource Planning
ESS	Environmental Supervision System
E3	Effective, Efficient, and Economical
FIP	Financial Incentive Program
GA	Genetic Algorithm
GIS	Geographical Information System
GPS	Global Positioning System
IRP	Incentive Reward Programme
IT	Information Technology
KB	Knowledge Base
KM	Knowledge Management
KMS	Knowledge Management System
LCA	Life Cycle Assessment
M&E	Materials and Equipments
PDA	Personal Digital Assistants
PERT	Programme Evaluation and Review Technique
RC	Reinforced Concrete
SPPI	Stochastic Process Pollution Index
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TTS	Trip-Ticket System
VLD	Vehicle Location Device
WAN	Wide Area Network

Chapter 1

Introduction

1.1 Overview

Adverse environmental impacts of construction such as soil and ground contamination, water pollution, construction and demolition (C&D) waste, noise and vibration, dust, hazardous emissions and odours, demolition of wildlife and natural features and archaeological destruction have been major concerns since early 1970s and received more and more attention in the construction industry, especially after the BS 7750 and the ISO 14001 Environmental Management System (EMS) were promulgated one after another in the 1990s.

However, although there have been many academic studies and professional practices for environmental management (EM) in construction, many of them were conducted in the form of regulations or guidelines. A literature review conducted by the authors of this book from the ASCE's CEDB (Civil Engineering Database) and the EI's Compendex® databases (refer to Table 3.6) revealed that only 2% of works provide quantitative methods in the total number of publications related to EM in construction in 2003. In this book, a set of quantitative methods, which finally composes an integrative prototype for supporting the EM in construction, is presented to support the EM in the lifecycle of a construction project.

1.2 Objectives of the book

The objective of this book is to describe an integrative quantitative approach to EM in construction. This objective has been achieved through five steps. First of all, an integrative methodology named E+ for dynamic environmental impact assessment (EIA) in construction is developed as a comprehensive framework. Next, four analytical methods are developed and integrated. These four methods include the construction pollution index (CPI) method to quantitatively evaluate and reduce pollution and hazard levels of processes and projects, the env.Plan method to evaluate environmental-consciousness of proposed construction plans and select the prime environmental-friendly construction plan, the incentive reward program (IRP) method to reduce on-site construction wastes through an incentive reward programme, and the Webfill method to promote C&D waste exchange in the local construction industry. Finally, the implementation of the integrative analytical approach is demonstrated by an experimental case study.

1.3 Organization of the book

There are eight chapters in this book. These chapters are organized according to their relationships with the objectives of the book. To start with the introduction to the integrative prototype for EM in construction, the need for quantitative approach to EM in construction is presented based on previous investigations on adoption and implementation of ISO 14001 EMS in construction enterprises in Australia, Hong Kong, mainland China, Singapore, United Kingdom and United States, etc. After the integrative prototype (named E+) for dynamic EIA in construction is described in Chapter 2, four practical analytical methods – including CPI method, env.Plan method, IRP method, and Webfill method, together with their working knowledge bases (KBs), which are essential components in the E+ prototype – are elaborated individually from Chapters 3 to 5. For the application of the E+ prototype to EM in construction, an experimental case study is then conducted to demonstrate the developed E+ prototype in Chapter 6. In addition to the E+ prototype and its essential components, conclusions and recommendations are then presented in Chapter 6 to summarize contributions and limitations of this book, and recommend further research and development for quantitative EM in construction. Finally, four appendices have been provided: a questionnaire for an investigation on the acceptability of the ISO 14001 EMS in the construction industry, a decision-making model for acceptance of the ISO 14001 EMS, sample waste exchange websites, and the function menu of Webfill (an e-commerce business plan). The abstract of each chapter is as follows.

1.3.1 Chapter 2: E+: An integrative methodology

The ISO 14001 EMS is not as widely acceptable as the EIA process in the construction industry, according to previous investigations. In order to demonstrate the acceptability of the ISO 14001 EMS in the construction industry, this chapter reports a remarkable disagreement between the rate of the ISO 14001 EMS registration and the rate of implementation of EIA in the Chinese construction industry. This disagreement indicates that the contractors there might not have really applied EM in construction projects. This hypothesis is then examined in this chapter by a questionnaire survey conducted among 72 main contractors in Shanghai, mainland China. Survey results indicate that there are five classes of factors influencing the acceptability of the ISO 14001 EMS, including governmental laws and regulations, technology conditions, competitive pressures, cooperation attitude, and cost–benefit efficiency. Reasons why approximately 81% of contractors surveyed are indifferent to the ISO 14001 EMS are then analysed based on the critical classes. A linear discriminant model for decision-making on whether to accept the ISO 14001 EMS for construction companies is consequently developed and provided in Appendix B.

On the other hand, the remarkable difference between the registration rate of ISO 14001 EMS and the implementation rate of EIA in the construction industry in mainland China also indicates that there may be little coordination between the implementation of EIA and EMS in construction projects in mainland China, and the EIA practice may not really serve as a tool to promote EM in construction. Since the China Environmental Protection Bureau enacted laws to implement the environmental supervision system in construction project supervision, contractors have to pay greater attention to adopt and implement EM in construction. According to the second emphatic factor based on the survey results, contractors paid greater attention to technology conditions on both construction and management and they thought the technology conditions can effectively enhance their working efficiency in EM in construction. Based on this consideration, this chapter presents an integrative methodology named E+ for dynamic EIA in construction, which integrates various EM approaches with a general EMS process throughout all construction stages in a construction project. As the E+ is designed to be a general tool to conduct EM in construction, it is expected to assist contractors to effectively, efficiently, and economically enhance their environmental performances all over the world.

1.3.2 Chapter 3: Effective prevention at pre-construction stage

To the authors' knowledge, there have been very few studies on integrating concerns of EM in the construction planning stage in particular. Construction planning involves the choice of construction technology, equipment and materials, the definition of work tasks, the layout of construction site, the estimation of required resources and durations for individual tasks, the estimation of costs, the preparation of a project schedule, and the identification of any interactions among the different work tasks, etc. (Horvath and Hendrickson 1998; Hendrickson and Horvath 2000). As a fundamental and challenging task, construction planning should not only strive to meet common concerns such as time, cost, and quality requirement, but also explore possible measures to minimize environmental impacts of the projects at the outset.

From this point of view, this chapter presents two quantitative methods for EM at pre-construction stage: the CPI method to quantitatively evaluate and reduce pollution and hazard levels of construction processes and projects, and the env.Plan method to quantitatively evaluate environmental-consciousness of proposed construction plan alternatives and thereafter select the prime environmental-friendly construction plan. Both CPI method and env.Plan method can greatly facilitate the application of the E+ prototype at the pre-construction stage.

The CPI method is a quantitative approach to EM on pollution and hazards potentially caused by construction projects in accordance with a proposed construction plan. The proposed CPI method is to assess and control the potential environmental problems upon implementation of a construction plan, and a method to calculate the CPI is originally put forward which provides a quantitative measurement of pollution and hazards caused by construction projects. In addition to the conception of the CPI, a practical method to comprehensively reducing construction pollution level during construction is put forward and examined. The CPI method is further applied in a commercial software environment, i.e. Microsoft Project©. A comparison study on the performance of CPI levelling between the normally used resource levelling method and genetic algorithm (GA) is also conducted. The parameters of CPI, i.e. pollution and hazards magnitude (h_i), are treated as a pseudo resource and integrated with a construction schedule. When the level of pollution for site operations exceeds the permissible limit identified by a regulatory body, the GA-enhanced levelling technique is used to reschedule project activities so that the level of pollution can be re-distributed and thus reduced. The GA-enhanced resource levelling technique is demonstrated using 20 on-site construction activities in a project. Experimental results indicate that the GA-enhanced resource levelling method performs better than the traditional resource levelling method used in Microsoft Project©. The proposed method is an effective tool that can be used by project managers to reduce the level of pollution at a particular period of time, when other control methods fail. The CPI is a primary component of the E+ prototype for reducing potential adverse environmental impacts during construction planning stage.

Although the CPI method is an effective and efficient approach to reducing or mitigating pollution level during the construction planning stage, the problem of how to select the best construction plan based on distinguishing the degree of its potential adverse environmental impacts is still unsolved. In the second section of this chapter, the authors review essential environmental issues and their characteristics in construction, which are critical factors in evaluating potential adverse environmental impacts of a construction plan. These environmental indicators are then chosen to structure two decision models for environmental-conscious construction planning by using an analytic network process (ANP), including a complicated model and a simplified model. The two ANP models named env.Plan can be applied to evaluate potential adverse environmental impacts of alternative construction plans. The env.Plan method is an important component of E+ prototype in selecting most environmental-friendly construction plan alternatives, and it is also a necessary complement of the CPI method in the E+ prototype.

1.3.3 Chapter 4: Effective control at construction stage

This chapter presents a group-based IRP method to encourage site workers to minimize avoidable wastes of construction materials by rewarding them according to the amounts and values of materials they saved. Based on the formulations of the IRP, bar-code technique is used to facilitate effective, efficient, and economical management of construction materials on site. In addition to the integration of the group-based IRP and the bar-code technique for reducing construction waste, an IRP-integrated construction management (CM) system is also introduced to avoid jerry-building and solve rescheduling problems due to rework because of quality failure. For the application of the IRP method, an experimental research is then conducted on a residential project in Hong Kong. Results from the experimental research demonstrate the effectiveness of the IRP in motivating workers to reduce construction wastes. In addition to the IRP method and its implementation, discussions on the relationship between construction waste reduction and time-cost performances, and difficulties and challenges of applying the IRP method are presented accordingly. The IRP method is a basic component of E+ prototype used for minimizing avoidable material wastes on construction site.

1.3.4 Chapter 5: Effective reduction at post-construction stage

Although the trip-ticket system (TTS) has been widely implemented to manage C&D waste in many countries for a long time, problems still exist in the landfill disposal of C&D waste. For example, it is reported that fees are difficult to collect from waste transporters for tipping the C&D waste at the landfill site in Hong Kong. Based on an examination on the flexibility of currently enacted TTS for reducing C&D waste, this chapter proposes an e-commerce model named Webfill in order to facilitate traditional TTS to effectively, efficiently, and economically manage C&D waste in macro scopes of the construction industry. The computational structure of the Webfill system is therefore described and the usefulness of the Webfill method is accordingly evaluated based on computer simulations which provide a direct comparison between the existing TTS and the Webfill-enhanced TTS. The Webfill method is an enhanced component of E+ prototype for reducing, reusing, and recycling C&D waste inside and outside a construction enterprise at post-construction stage when C&D waste has been inexorably generated.

1.3.5 Chapter 6: Knowledge-driven evaluation

This chapter demonstrates an integrative application of the E+ prototype for dynamic EIA in construction illustrated in Chapter 2 by using an experimental case study, in which various quantitative EM methods described in Chapters 3–5 are integrated with a general ISO 14001 EMS process throughout all construction stages in a construction project. Besides the demonstration of the E+ prototype, the experimental case study used in this chapter also indicates that it is necessary to further develop the integrative prototype to be a Web-based E+

environment to effectively, efficiently, and economically undertake and enhance EM in construction.

1.3.6 Appendices

The appendix section consists of four appendices: Appendix A: a questionnaire for investigating the acceptability of the ISO 14001 EMS in the construction industry, Appendix B: a decision-making model for acceptance of the ISO 14001 EMS, Appendix C: sample waste exchange websites, and Appendix D: the function menu of Webfill (an e-commerce business plan). Appendices A and B complement the investigation on the acceptability of ISO 14001 EMS in the construction industry with a questionnaire and corresponding statistic analysis. Appendix C provides a list of 36 websites related to C&D waste exchange from which the e-commerce model for the Webfill method is developed. Appendix D illustrates the function menu of Webfill (an e-commerce business plan).

Chapter 2

E+: An integrative methodology

2.1 Introduction

Since September 1996, when the ISO 14000 series was first issued, environmental management systems (EMSs) have been received in the construction industry globally (ISO 2001), and have become a research and development area in construction management (Kein *et al.* 1999; Ofori *et al.* 2000; Tse 2001). The ISO survey in 2001 showed that there is a continuing strong growth of ISO 14001 EMS registration in the construction industry; for instance, the number of registered companies increased from 298 as at the end of 1998, to 500 as at the end of 1999, and then up to 1035 as at the end of 2000 (ISO 2001). However, three statistical figures from mainland China indicate that the EMS has not been prevalent in the construction industry there. The first figure is the percentage of environmental certificates awarded to Chinese enterprises versus total environmental certificates awarded to enterprises worldwide, which is as low as 2.23% (ISO 2001); the second figure is the percentage of environmental certificates awarded to Chinese construction enterprises versus total environmental certificates awarded to Chinese enterprises, which is as low as 7.65% (ISO 2001); and the third figure is the percentage of the construction enterprises that have been awarded environmental certificates versus total governmental registered construction enterprises in mainland China, which is as low as 0.083% (CCEMS 2001; CEC 2001; CEIN 2001a; CACEB 2002). These statistical data indicate that the construction enterprises have not fully accepted the ISO 14000 series in mainland China.

By contrast, a higher implementation rate of environmental impact assessment (EIA) in construction projects in mainland China is encountered from another statistical analysis (China EPB 2000/2001). The EIA of construction projects is the process or technique of identifying, predicting, evaluating, and mitigating the biophysical, social, and other relevant environmental effects of development proposals or projects prior to major decisions being taken and commitments made (IAIA 1997; European Commission 1999; landscape Institute with IEMA 2002). According to the *Official Report on the State of the Environment in China 2000* (China EPB 2000/2001), the implementation rates of EIA were 90.4% in 1999 and 94.8% in 2000. A further investigation on the implementation rate of

EIA in mainland China indicates that the average EIA rate from 1995 to 1997 is 82% (a mean of three yearly average EIA rates, which are 79% in 1995, 81% in 1996, and 85% in 1997). Comparing with what it was in 1999 and 2000, the implementation rate of EIA is rising, although it varies in different municipalities and provinces in a range from 46 to 100%. It is obvious that the EIA rate is much higher than the implementation rate of the ISO 14000 series in mainland China.

The statistical data indicates that the ISO 14000 series have not yet been widely implemented in the Chinese construction industry and the problem of whether contractors have really accepted the standard also emerges. In order to further verify the observation and understand the reasons that hinder the acceptance of the standard, a questionnaire survey focusing on the adoption and implementation (A&I) of EMS and the ISO 14000 series has been conducted over 100 selected construction companies in Shanghai, which is selected as a representative city in mainland China. Reasons why some contractors surveyed resist the A&I of the ISO 14000 series ($ISO\ 14Ks_{A\&I}$) are then analysed and useful conclusions, including a discriminant model for decision-making on ISO 14000 acceptance, are generated. A Microsoft Excel® spreadsheet is adopted to apply the discriminant model.

2.2 Background

Environmental management in construction has received more and more attention since the early 1970s. For example, studies on noise pollution (U.S.EPA 1971), air pollution (Jones 1973), and solid waste pollution (Skoyles and Hussey 1974; Spivey 1974a,b) from construction sites were individually conducted in the early 1970s. Although the expression “EM in construction” came out in the early 1970s after the U.S. National Environmental Policy Act of 1969 was enacted (Warren 1973), the concept of EM in construction was introduced in the late 1970s, when the role of environmental inspector was defined in the design and construction phases of projects to provide advice to construction engineers on all matters in EM (Spivey 1974a,b; Henningson 1978). However, there had been little enthusiasm for establishing an EMS in construction organizations until two important standards, BS 7750 (issued in 1992) and the ISO 14000 series (issued in 1996), were promulgated to guide the construction industry from passive construction management on pollution reduction to active EMS for pollution prevention.

In the 1990s, the Construction Industry Research and Information Association (CIRIA) conducted a series of reviews on environmental issues and have undertaken initiatives relevant to the construction industry after the introduction of BS 7750 (Shorrock *et al.* 1993; CIRIA 1993, 1994a,b, 1995; Guthrie and Mallett 1995; Petts 1996). Thereafter, research efforts for EM have also been put into the implementation of EMS and the accreditation of ISO 14001 EMS by authoritative institutions in the construction industry, including the CIOB (Clough and Antonio 1996), the FIDIC (1998), the Construction Policy Steering Committee (CPSC 1998), and the CIRIA (Uren and Griffiths 2000).

In order to assess the extent of EMS implementation within the construction industry, several investigations have been conducted. For example, Kein *et al.* (1999) conducted a field study in Singapore to assess the level of commitment of ISO 9000-certified construction enterprises to EM. They found that contractors in Singapore were aware of the merits of EM, but were not instituting systems towards achieving it; Ofori *et al.* (2000), also in Singapore, then conducted a survey to ascertain the perceptions of construction enterprises on the impact of the implementation of the ISO 14000 series on their operations. Major problems were identified, such as the shortage of qualified personnel, lack of knowledge of the ISO 14000 series, indistinct cost–benefit ratio, disruption and high expenses on changing traditional practices, and resistance from employees, etc.; the CIRIA (1999) led a self-completion questionnaire survey of the state of environmental initiatives within the construction industry and of sustainability indicators for the civil engineering industry in the United Kingdom; Tse (2001) conducted an independent questionnaire survey in the Hong Kong construction industry to gain a further understanding of the difficulties in implementing the ISO 14000 series; Lo (2001), also in Hong Kong, made an effort to identify nine critical factors for the implementation of ISO 14001 EMS in the construction industry based on critical factors drawn from an investigation in another industry; and the CPSC (2001), in Australia, conducted a questionnaire survey of the New South Wales construction industry on EM with industry leaders. All these questionnaire surveys aimed to clarify the real situations in $ISO\ 14Ks_{A\&I}$ in local construction industries.

One important contribution of these surveys is that researchers have gained useful insights into the problems and difficulties of implementing the ISO 14000 series. Their survey results provide useful information not only for improving efficiency on EMS implementation but also for developing the EMS itself, focusing on effective EM in the construction industry. For example, Tse (2001) has found four major obstacles in implementing the ISO 14000 series in Hong Kong's construction industry, including lack of government pressure, lack of client requirement or supports, expensive implementation cost, and difficulties in managing the EMS with the current sub-contracting system. One cannot easily draw such constructive conclusions in detail without such a kind of survey. However, what originally impelled us to an investigation on the acceptability of the ISO 14000 series in mainland China was not the advantage of a survey even though there is little published research work in this area, but the remarkable disagreement between the rate of ISO 14001 EMS registration and the rate of EIA implementation in Chinese construction industry. As stated previously, the remarkable deviation between the two rates indicates that the contractors in mainland China may not have really applied EM in construction projects. In order to verify this hypothesis, a questionnaire survey was conducted and details of the questionnaire survey are described below.

2.3 A questionnaire survey

2.3.1 Data collection

The methodology adopted for this study involves the use of a structured questionnaire (see Appendix A) and a statistical analysis. Shanghai was selected as a representative city. As one of the most industrialized Chinese cities, Shanghai is halfway along the eastern coastline of mainland China. It is a municipality with an urban population of 9.6 million, and plays an essential role in national socio-economic affairs; furthermore, Shanghai is one of the areas where there have been large numbers of construction projects in mainland China in the past several years (China NBS 2000).

In mainland China, construction enterprises are divided into three types: main contractors, specialized contractors, and labour contractors (MOC 2001a,b,c). Each type is further divided into different classes according to the characteristics of construction projects and technological demands. And each class is then divided into different grades with specified qualifications to individual companies. At present, there are five grades of main contractors. They are Special Grade, and Grade-1 to Grade-4. The population of the survey group consists of 100 main building contractors randomly selected from Shanghai, including 50 Grade-1 qualified contractors and 50 Grade-2 qualified contractors.

Hundred copies of the questionnaire were distributed to the main contractors in Shanghai, with whom the authors were acquainted in April 2001. By the end of October 2001, 72 usable responses were received. This represents 1.5% of contractors in the Shanghai construction industry. All survey data accumulated were analysed using a standard version of SPSS® 11.

2.3.2 Overall status

Among these 72 construction companies, 2 companies have ISO 14001 EMS registrations, 1 company is under assessment for registration, 11 companies are willing to apply for registration, and 58 companies do not want to apply. These results indicate that the ISO 14000 series has only been accepted by 19% of the contractors surveyed, while others (81%) gave out their indifference to the ISO 14000 series.

2.3.3 Main reasons for indifference

The reasons for indifference to the ISO 14000 series are summarized in Table 2.1. The acceptability of the ISO 14000 series is examined separately in terms of A&I in the questionnaire survey (see Parts 6 and 7 in Appendix A), as adoption

Table 2.1 Potential influential reasons for indifference to the ISO 14000 series

(a) Reasons for not adopting the ISO 14000 series

Class	*Reason Item*	*Grade Mean*	*Grade Rank*
1	Lack of governmental administrative requirement on adopting the ISO 14000 series	9.0	1
	Lack of governmental encouragement on financial subsidies, e.g. tax deduction/return	8.5	2
	Lack of governmental encouragement on non-financial allowance	8.4	3
2	Lack of reliable consultant companies on tutorship of adoption of the ISO 14000 series	7.5	6
3	Lack of competitive pressure from domestic construction industry	7.1	7
	Lack of competitive pressure from international construction industry within WTO	7.0	8
4	Lack of internal initiative consciousness on implementation of EMS	8.0	4
5	High cost of implementation of ISO 14001 EMS (About RMB 0.3M)	7.6	5
	High cost of ISO 14001 EMS assessment, certification, and maintenance	6.8	9
	Additional cost of human resource on adopting and implementing the ISO 14000 series	6.8	9
	High cost of ISO 14001 registration (About RMB 50,000)	6.6	10
–	Additional cost of reorganization on adopting and implementing the ISO 14000 series	6.3	11
–	The necessity of management involvement on adopting the ISO 14000 series	6.3	11
–	Interrupt and adjustment of construction processes on implementing the ISO 14000 series	6.1	12
–	Entire employees' training and education before implementing ISO 14001 EMS	6.0	13
–	Various additional EM documents on adopting ISO 14000 series	6.0	13
–	Lack of requirement and pressure from clients or suppliers	6.0	13
–	Lack of expectation from clients or suppliers	6.0	13
–	Additional cost on training functionaries inside company	5.9	14
–	Lack of intention to establish enterprise's internal ISO 14000 based EMS	5.6	15
–	Less encouraging subcontractors to adopt ISO 14000 series for improving EM	5.6	15
–	Additional cost of failure on adopting ISO 14001 EMS	5.2	16

Table 2.1 (Continued)

(b) Reasons for not implementing the ISO 14000 series

Class	*Item*	*Grade Mean*	*Grade Rank*
1	Lack of pressure from the government	8.0	4
2	Multifarious documental operation process of the ISO 14000 series	9.0	2
	Destitute of applicability of the ISO 14000 series in construction enterprises	8.5	3
	Lack of suitable technology and material for environmental protection	8.0	4
3	Lack of pressure from the competitors inside construction industry	6.5	6
	No competitors implemented the ISO 14000 series first inside construction industry	6.0	7
	Lack of pressure from the clients	5.5	8
4	Lack of correspondence and cooperation of design and construction	9.0	2
	Poor employees' attitude towards cooperation on implementing the ISO 14000 series	9.0	2
	Poor administrators' attitude towards cooperation on implementing the ISO 14000 series	9.0	2
	Poor subcontractors' attitude towards cooperation on implementing the ISO 14000 series	9.0	2
	Poor suppliers' attitude towards cooperation on implementing the ISO 14000 series	7.5	5
5	Additional cost of implementation of ISO 14001 EMS	9.5	1
	Impacts and additional expense of construction on interruption and adjustment	9.5	1
	Costly expense on implementation	9.5	1
–	Success/failure on employees' training and education inside enterprise	8.0	4
–	Success/failure on maintenance and continuous assessment of the ISO 14000 series	8.0	4
–	Success/failure on administrator's training and education inside enterprise	8.0	4
–	Success/failure on combination with other EMS inside enterprise	6.5	4
–	Success/failure on adjustment of organizational structure inside enterprise	6.0	7

Notes

Class 1 = Governmental regulations; Class 2 = Technology conditions; Class 3 = Competitive pressures; Class 4 = Cooperative attitude; Class 5 = Cost–benefit efficiency.

means only to get an ISO 14001 EMS registration, while the implementation is to carry out the EMS after registration, and some contractors who gain ISO 14001 certificates might not carry out a qualified EMS up to the requirements of the ISO 14000 series. Table 2.1a gives reasons for indifference to adopting the ISO 14000 series, and Table 2.1b gives reasons for indifference to implementing the ISO 14000 series.

In order to find critical factors that influence the adoption and the implementation of the ISO 14000 series, reasons in Table 2.1a and Table 2.1b are assorted into classes according to their coherence, and five classes are identified: governmental command-and-control regulations on $ISO\ 14Ks_{A\&I}$ (governmental regulations), applied environmental-friendly technology conditions in construction and management (technology conditions), competitive pressures from both domestic and foreign trades (competitive pressures), attitude towards cooperation with an EM-seeking enterprise on $ISO\ 14Ks_{A\&I}$ (cooperative attitude), and cost–benefit efficiency on $ISO\ 14Ks_{A\&I}$ (cost–benefit efficiency). All items are ranked according to their mean score grades, which are calculated with corresponding scores from respondents who are indifferent to the adoption of the ISO 14000 series. The average grades of each of the five classes are then determined by using grade means of each corresponding reason in the class.

First, the main reasons for indifference to adopting the ISO 14000 series (refer to Table 2.1a) show that those respondents score highly in a sequence on governmental regulations (Ranks 1 to 3 with an average grade of 8.6), cooperative attitude (Rank 4 with an average grade of 8.0), technology conditions (Rank 6 with an average grade of 7.5), competitive pressures (Ranks 7 and 8 with an average grade of 7.1), and cost–benefit efficiency (Ranks 5, 9, and 10 with an average grade of 7.0).

In terms of indifference to implementation of ISO 14000 series, major reasons in the classes (as shown in Table 2.1b) were identified, which include the cost–benefit efficiency (Rank 1 with an average grade of 9.5), cooperative attitude (Ranks 2 and 5 with an average grade of 9.3), technology conditions (Ranks 2, 3, and 4 with an average grade of 8.6), governmental regulations (Rank 4 with an average grade of 8.0), and competitive pressures (Ranks 6, 7, and 8 with an average grade of 6.0).

Combining the results of Tables 2.1a and 2.1b, the histograms which indicate the opinions of companies surveyed for not adopting and implementing the ISO 14000 series, as shown in Figure 2.1, were obtained.

Additionally, in order to test whether a mean grade differs from a given hypothesized test value in the corresponding column in Tables 2.1a and 2.1b, the one-sample t test method is employed in every calculation on an individual potential influential factor. At the 95% confidence level, the critical value of t with 57 degrees of freedom (i.e. $n - 1 = 58 - 1$) is 2.11. Therefore, as the absolute value of t (here $t = 0$) is less than $+2.11$, it is concluded that the null hypothesis (mean grade) could not be rejected.

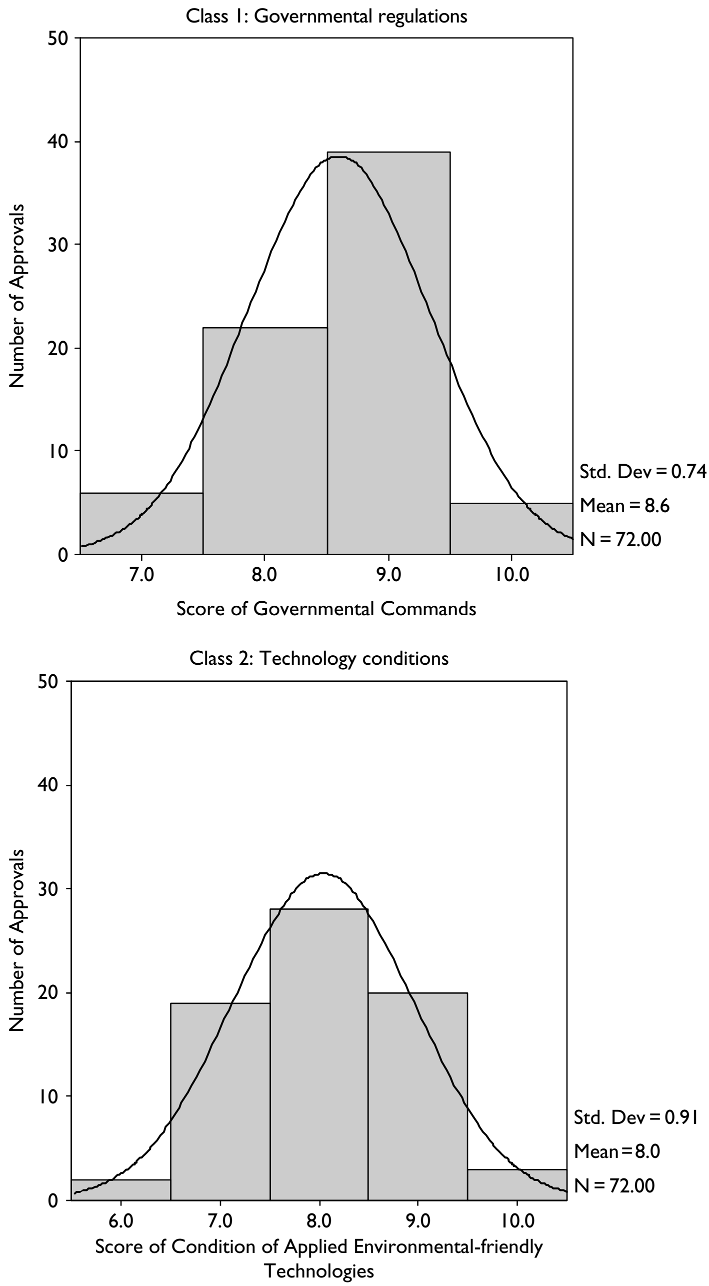
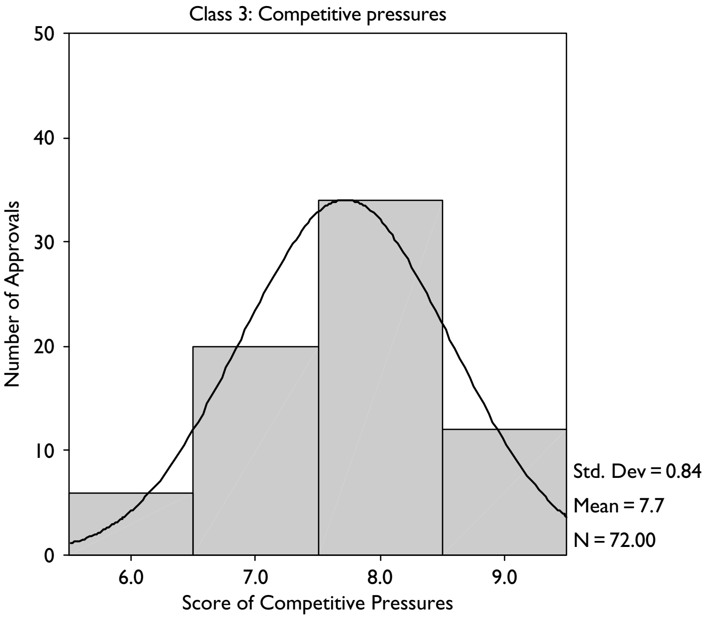


Figure 2.1 Class histograms for ISO 14000's acceptability with total 72 respondents.



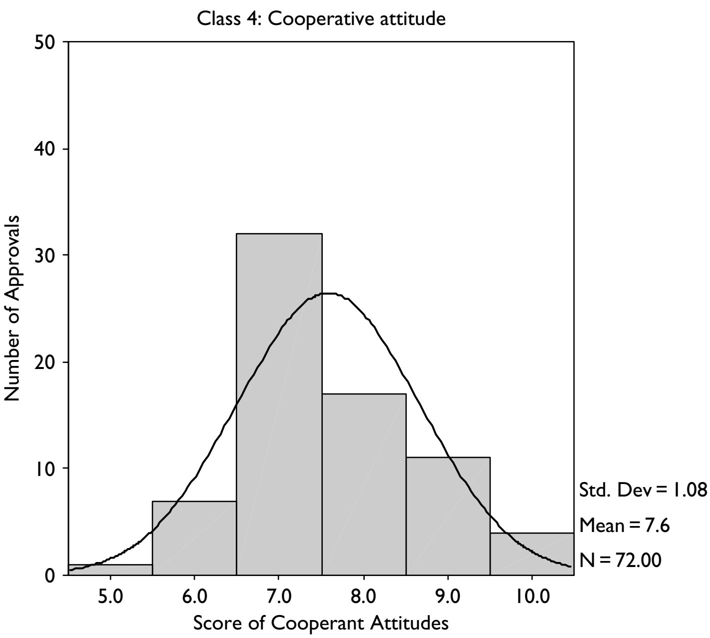
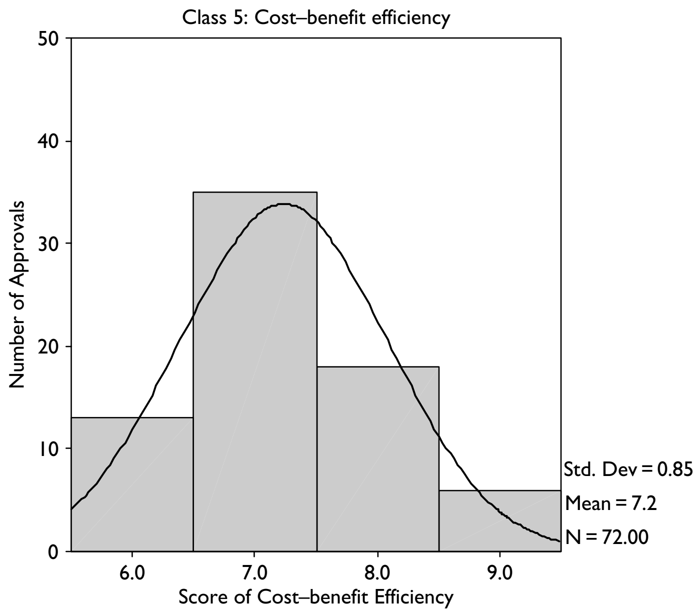


Figure 2.1 (Continued).



Ranks of top five classes

Ranking with 58 indifferentists

1 Governmental regulations (Mean grade is 8.4)
2 Technology conditions(Mean grade is 8.2)
3 Cooperative attitude (Mean grade is 7.9)
4 Cost–benefit efficiency (Mean grade is 7.4)
5 Competitive pressures (Mean grade is 7.3)

Ranking with 14 accepters

1 Governmental regulations (Mean grade is 8.5)
2 Technology conditions(Mean grade is 7.9)
3 Competitive pressures (Mean grade is 7.8)
4 Cooperative attitude (Mean grade is 7.4)
5 Cost–benefit efficiency (Mean grade is 7.1)

Ranking with 72 respondents

1 Governmental regulations (Mean grade is 8.6)
2 Technology conditions(Mean grade is 8.0)
3 Competitive pressures (Mean grade is 7.7)
4 Cooperative attitude (Mean grade is 7.6)
5 Cost–benefit efficiency (Mean grade is 7.2)

Notes

1 Alpha is a reliability coefficient for rejecting the null hypothesis when in fact the null hypothesis is true.

2 Reliability coefficients of the top five classes: $\alpha = 0.69$, Standardized item $\alpha = 0.70$.

Figure 2.1 (Continued).

2.4 Examinations

According to the survey results, the critical factors for not adopting and implementing the ISO 14000 series are characterized by five classes: governmental regulations, technology conditions, competitive pressures, cooperation attitude, and cost–benefit efficiency. These critical factors are now further analysed.

2.4.1 Governmental regulations

The governmental regulations include all kinds of governmental command-and-control ordinances and regulations on encouraging contractors to adopt and implement EMS. In the survey, the governmental regulations are divided into three scopes: administrative requirement on adopting and implementing EMS in construction industry, encouragement of financial subsidies (e.g. tax deduction or repay), and encouragement of non-financial allowance. Analysing data regarding these three kinds of governmental regulations shows that all Pearson's correlation coefficients (0.890 between administrative requirement and financial encouragement, 0.420 between financial and non-financial encouragement, and 0.399 between administrative requirement and non-financial encouragement) are significant at the 0.01 level (2-tailed). Frequencies of each kind of governmental regulation above their mean grades are 76.2, 76.2, and 80.0%; and these frequencies are quite similar on approaching 80%. Moreover, a trend analysis between the governmental regulations and the ISO 14000 series' acceptability indicates that contractors who give higher score to governmental regulations would have less intention to accept the ISO 14000 series. The survey results indicate that the government plays an important role in promoting $ISO\ 14Ks_{A\&I}$, and contractors would prefer to be indifferent to the ISO 14000 series if there were insufficient governmental command-and-control regulations on it.

The survey results offer a conclusion similar to those of the three previous surveys on $ISO\ 14Ks_{A\&I}$ in the construction industry in Hong Kong (Tse 2001) and Singapore (Kein *et al.* 1999; Ofori *et al.* 2000) in that contractors would ignore to adopt and implement the ISO 14000 series directly if there were lack of pressure from the government. The effect of governmental regulations is also reflected in the fact that the high implementation rate of EIA in mainland China is because the *Managerial Ordinance on Environmental Protection of Construction Project* (SC of China 1998) stipulates that all new construction projects must apply for environmental impact approval following an approval procedure of EIA report/form or Ei form before construction. More than 90% of new construction projects have been undertaken according to the EIA procedure and received approval annually in mainland China since the ordinance was issued (China EPB 2001). Moreover, a literature review shows that the governmental regulations particularly affect the number of ISO 14001 certified contractors in Hong Kong.

In the past four years, the number of ISO 14001–certified contractors in Hong Kong was 4 in 1998, 7 in 1999, 4 in 2000, 22 in 2001, and 2 in early 2002 (HKEPD 2002). These numbers coincide with the governmental regulations on promoting the ISO 14000 series issued twice, in later 1996 and early 2000 (HKPC 1996, 2000); for example, there were 15 ISO 14001–certified contractors after the first promotion in 1996 and the figure increased to 39 owing to the second promotion in 2000.

Unfortunately, there have been no governmental regulations on promoting the ISO 14000 series nationally or locally in the Chinese construction industry since 1996, and contractors with less consciousness on environmental protection in mainland China can thus be indifferent to the EMS without any liability. For example, although the Environmental Protection Bureau of China has established seven National Demonstration Districts to display the benefits of implementing ISO 14001 EMS since 1998 (China EPB 2002), there has been no ISO 14000 series–related requirement or restriction for contractors to tender projects (China EPB 2001). Moreover, in the 10th five-year plan of the Ministry of Construction in China (CMC 2000), no environmental-friendly construction technology is promoted. It is thus not surprising to see that near by 81% of contractors were indifferent to the $ISO\ 14Ks_{A\&I}$ in the survey.

2.4.2 Technology conditions

Technology conditions refer to the level of environment-friendly or resource-efficient (NAHB Research Center 1999) technologies for reducing negative environmental effects in construction. In the survey, these technologies are divided into three types, the first type includes the use of technologies in order to get accreditation of ISO, the second type includes technologies used for implementing the ISO 14000 series (Technology B), and the third type includes technologies used by a company to reduce negative environmental impacts, although the company does not accept the ISO 14000 series (Technology C). Analysing data regarding these three types of technologies shows that all the Pearson's correlation coefficients (0.469 between Technology A and Technology B, 0.449 between Technology A and Technology C, and 0.442 between Technology B and Technology C) are significant at the 0.01 level (2-tailed). Frequencies of the three types of technologies above mean grades are 76.1, 66.7, and 57.1%, all of which are above 50%. Moreover, a trend analysis between the technology condition and the ISO 14000 series' acceptability indicates that contractors who gave higher scores to the technology condition would be more likely to accept the ISO 14000 series. The survey results indicate that technologies are an important means for adopting and implementing the ISO 14000 series and contractors would prefer to accept the ISO 14000 series if there were sufficient technologies to help them to control and reduce the negative environmental impacts in construction.

2.4.3 Competitive pressures

Competitive pressures include pressures from the competitors of both the domestic and international markets on *ISO* $14Ks_{A\&I}$. The survey divides the competitive pressures into two scopes: domestic competitive pressure and international competitive pressure. Analysing data regarding these two scopes of competitive pressures shows that the Pearson's correlation coefficient (0.558 between domestic competitive pressure and foreign competitive pressure) is significant at the 0.01 level (2-tailed). Frequencies of the two scopes of competitive pressures above mean grades are 64.3 and 61.9%, which are above 60%. Moreover, a trend analysis between the competitive pressures and the acceptability of the ISO 14000 series indicates that contractors who give higher score to the competitive pressures would be more likely to accept the ISO 14000 series. The survey results indicate that competitive pressure is an important consideration when contractors decide whether to adopt and implement the ISO 14000 series, and contractors will accept the ISO 14000 series if there are sufficient competitive pressures.

In the past five years, construction companies in mainland China met with increasing competition from foreign construction companies in the domestic market. According to the statistical data from the China National Bureau of Statistics, the proportion of foreign construction companies has grown with an average rate of 10.7% since 1996, while the proportion of domestic construction companies has shrunk with the rate of 2.9% (China NBS 1998/2000). This indicates that contractors in mainland China are facing severe competition from their international counterparts, especially in the next five to ten years after China's accession to WTO and many important civil infrastructure projects will be tendered internationally (CEIN 19/03/2001).

Unfortunately, contractors involved in the survey have not yet realized the competitive pressure and the trend of globalization, as most of them have been largely accustomed to focusing on competition with their domestic peers.

2.4.4 Cooperative attitude

Cooperative attitude reflects the willingness of people in *ISO* $14Ks_{A\&I}$. In the survey, the cooperative attitude is divided into four scopes: cooperative attitude from designers, cooperative attitude from workers, cooperative attitude from administrators, and cooperative attitude from subcontractors. Analysing data regarding these four scopes of attitude on cooperation shows that the Pearson's correlation coefficients (0.803 for cooperative attitude among workers, administrators, and subcontractors, 0.661 for cooperative attitude between employees and designers, and 0.557 for cooperative attitude among designers, administrators, and subcontractors) are significant at the 0.01 level (2-tailed). Frequencies of the four scopes of attitude on cooperation above mean grades are 59.5, 50.0, 52.4, and 52.4%, all of which are above 50%. Moreover, a trend analysis between the cooperative attitude and the acceptability of the ISO 14000 series indicates that contractors who give higher score to the cooperative attitude would have greater intention of accepting the ISO 14000 series. The survey results indicate that the cooperative attitude towards $ISO\ 14Ks_{A\&I}$ also affects the progression of EMS, and contractors would have accepted the ISO 14000 series if there had been satisfactory cooperation on EMS both inside and outside their companies.

2.4.5 *Cost–benefit efficiency*

Cost–benefit efficiency includes all concerns regarding benign cost–benefit circulations on $ISO\ 14Ks_{A\&I}$ inside a construction enterprise. In our survey, the concerns of cost–benefit efficiency are divided into three main scopes: costs for registration and maintenance of ISO 14001 EMS certification, costs for implementation of ISO 14001 EMS, and benefits from the $ISO\ 14Ks_{A\&I}$. Analysing data regarding these three scopes of concerns in cost–benefit efficiency shows that the Pearson's correlation coefficients (0.561 between cost on registration and cost on implementation, 0.701 between cost and benefit of $ISO\ 14Ks_{A\&I}$) are significant at the 0.01 level (2-tailed). Frequencies of the three scopes of concerns on cost–benefit efficiency above mean grades are 50.0, 57.1, and 54.8%, all of which are above 50%. Moreover, a trend analysis between the cost–benefit efficiency and the ISO 14000 series' acceptability indicated that contractors who give higher score to the cost–benefit efficiency would have less intention to accept the ISO 14000 series. The survey results indicate that the indistinct cost–benefit efficiency obstructs the progression of the ISO 14000 series and contractors prefer to see a higher cost–benefit efficiency on the $ISO\ 14Ks_{A\&I}$.

Our survey results encounter another similar conclusion with the three previous surveys as detailed before in that contractors would hesitate to adopt and implement the ISO 14000 series if the cost is high. One way for small and medium-sized enterprises to reduce the cost is to form a network and establish a joint EMS in accordance with the ISO 14000 series. This route to achieve the ISO 14000 series has been proved effective at the Hackefors Industrial District in Sweden (Ammenberg *et al.* 2000).

2.5 The E+

2.5.1 *Introduction*

The EIA of construction projects is a process of identifying, predicting, evaluating, and mitigating the biophysical, social, and other relevant environmental effects of development proposals or projects prior to major decisions being taken and commitments made (IAIA 1997). According to the *Official Report on the State of the Environment in China 2001* (China EPB 2002), the annual implementation rate of EIA for construction projects was 97% in 2001 in mainland China. In addition, a further investigation on the implementation rate of EIA in mainland China indicates that the average EIA implementation rate from 1995 to 2001 is 88%, with an increasing rate of 23% (China EPB 2002).

On the other hand, three statistical figures from mainland China indicate that the EMS may not have been prevalent in the construction industry there; and they are given below.

- The first figure is the percentage of environmental certificates awarded to Chinese enterprises versus total environmental certificates awarded to enterprises worldwide, which is as low as 2% (ISO 2002);
- The second figure is the percentage of environmental certificates awarded to Chinese construction enterprises versus total environmental certificates awarded to Chinese enterprises, which is as low as 8% (ISO 2002);
- The third figure is the percentage of the construction enterprises that have been awarded environmental certificates versus total governmental registered construction enterprises in mainland China, which is as low as 0.1% (CACEB 2002; CEIN 2002).

It is obvious that implementation rate of EIA is much higher than the implementation rates of the ISO 14000 series in the construction industry in mainland China. These statistical figures also indicate that most construction enterprises have not yet adopted or accepted the ISO 14000 series in mainland China. Because of the disagreement between the implementation rates of EIA and EMS, there may be little coordination between the EIA process and EMS implementation in construction projects, and thus EIA may not really serve as a tool to promote EM in the construction industry in China. As a result, adverse environmental impacts such as noise, dust, waste, and hazardous emissions still occur frequently in construction projects in spite of their EIA approvals prior to construction.

However, this situation is expected to improve in the near future. The China Environmental Protection Bureau has enacted laws, in December 2002, to implement the environmental supervision system (ESS) in construction project management (China Environment Daily 16/12/2002). Although this supervision system had been carried out in 13 pilot construction projects only since 2002, it is suggested that contractors in mainland China have to pay greater attention to EM in project construction in future, and prepare to actually adopt and implement EM in construction in the near future.

To find out the main obstacles to implementing the ISO 14000 in the construction industry in mainland China, a questionnaire survey was conducted in 2001 among representative contractors in Shanghai, a representative city, and five key factors were identified. These five factors are (1) governmental command-and-control ordinances and regulations on encouraging contractors to adopt and implement EMS, (2) technology conditions for environment-friendly or resource-efficient construction, (3) competitive pressures from the competitors of both the domestic and international markets on adopting and implementing the ISO 14000 series, (4) cooperative attitude towards adopting and implementing the

ISO 14000, and (5) cost–benefit efficiency on adopting and implementing the ISO 14000 (Chen and Li *et al.* 2004b). According to the survey results, contractors in mainland China are most interested in technology conditions such as construction techniques and construction management approaches that can assist field engineers to reduce adverse environmental impacts in terms of the requirements of environmental ordinances and laws.

As can be seen from statistic figures and the questionnaire survey, the implementation of either the EMS or the ESS requires additional EM approaches as practicable as the EIA approach, which is popular and easier to use by contractors. For that reason, this chapter attempts to transplant a standard EMS process into a static EIA process, which is currently adopted in mainland China, to derive a dynamic EIA process. The EMS-based dynamic EIA process presented in this chapter, named as E+, is an integrative methodology which integrates practicable EM approaches into an ISO 14001 EMS process throughout a whole construction cycle in a construction project, and it is expected to be able to assist contractors to effectively and efficiently enhance their EM performance in China.

2.5.2 A conception model of the E+

The E+ is an integrative methodology for EM in construction projects, using which a dynamic EIA process can be effectively and efficiently applied during construction. The successful implementation of an EMS in construction projects requires far more than just the apparent prevention and reduction of adverse or negative environmental impacts in a new project and its construction process development cycles during pre-construction stage, continuous improvement of the EM function based on institutionalization of change throughout an onsite organization to reduce pollution during mid-construction stage, or efficient synergisms of pollution prevention and reduction such as waste recycle and regeneration in construction industry during mid-construction and post-construction stages. It necessitates a complete transformation of the construction management in an environmentally conscious enterprise, such as changes in management philosophy and leadership style, creation of an adaptive organizational structure, adoption of a more progressive organizational culture, revitalization of the relationship between the organization and its customers, and rejuvenation of other organizational functions (i.e. human resources engineering, research and development, finance, and marketing, etc.) (Azani 1999). In addition to the transformation for EM in construction enterprises, the integrative methodology, E+, for the effective implementation of EM in all phases of construction cycle including the pre-construction stage, the mid-construction stage, and the post-construction stage is necessarily activated, together with other rejuvenated construction management functions such as human resources, expert knowledge, and synergetic effect.

There are already some approaches to effectively implementing the EM onsite at different construction stages. For example, for the pre-construction stage, a CPI approach, which is a method to quantatively measure the amount of pollution and hazards generated by a construction process and construction project during construction, can be utilized by indicating the potential level of accumulated pollution and hazards generated from a construction site (Chen, Li and Wong 2000), and by reducing or mitigatingpollution level during the construction planning stage (Chen and Li *et al.* 2002); in addition to the CPI approach, a life-cycle assessment (LCA) approach for material selection (Lippiatt 1999), and a decision programming language (DPL) approach for environmental liability estimation (Jeljeli and Russell 1995), etc. also provide computable methods for making decision on EM at pre-construction stage; for the mid-construction stage, a crew-based incentive reward program (IRP) approach, which is realized by using bar-code system, can be utilized as an on-site material management system to control and reduce construction waste (Chen and Li *et al.* 2002a); for the post-construction stage, an online waste exchange (Webfill) approach which is further developed into an e-commerce system based on the trip-ticket system for waste disposal in Hong Kong can be utilized to reduce the final amount of C&D waste to be landfilled (disposed of the C&D waste in a landfill) (Chen and Li *et al.* 2003a). Although these approaches to EM in project construction have proved effective and efficient when they are used in a corresponding construction stage, it has also been noticed that these EM approaches can be further integrated for a total EM in construction based on the interrelationships among them. The integration can bring about not only a definite utilization of current EM approaches but also an improved environment for contractors to maximize the advantages of utilizing current EM approaches due to sharing EM-related information or data.

As mentioned above, the EMS is not as acceptable as EIA in mainland China partly due to the lack of efficient EM tools, and the tendency of EM in construction is to adopt and implement the EMS after the EIA report/form of a construction project is approved. As a result, the dynamic EIA process for contractors to enhance their environmental performance in mainland China, which integrates all necessary EM approaches available currently, just appropriates to the occasion.

The proposed E+ aims to provide high levels of insight and understanding regarding the EM issues related to the management in a construction cycle. In fact, current EIA process applied in mainland China is mainly conducted prior to the pre-construction stage of a construction project, when a contractor is required to submit an EIA report/form based on the size and significance of the project and the EIA process for the mid-construction stage is seldom conducted in normalized forms. Due to the alterability of the environmental impacts in the construction cycle, the commonly encountered static EIA process prior to construction cannot accommodate the implementation of the EMS in project construction, and a dynamic EIA process is thus designed for the E+. In addition, current EM approaches are to be combined with a frame of the EMS (a process of the EMS including issuing environmental policies, planning, implementation and

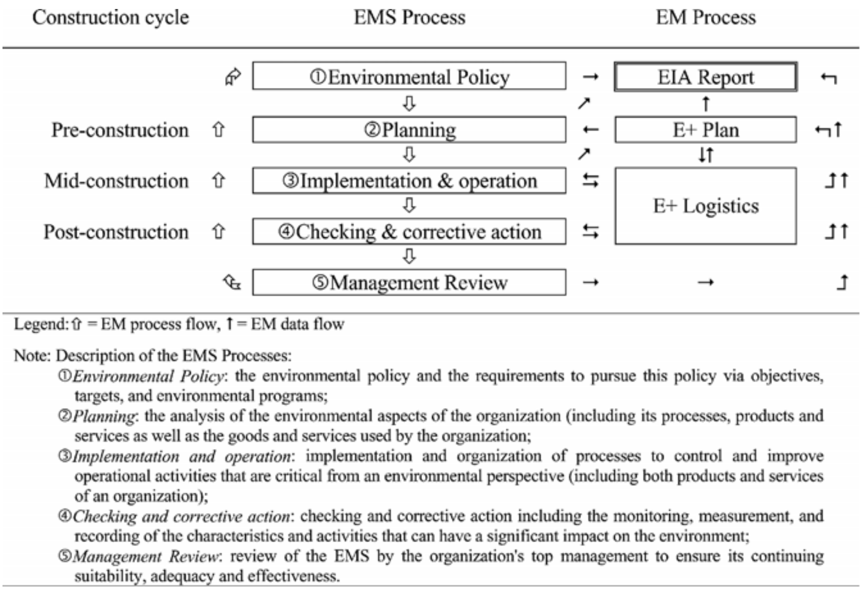


Figure 2.2 A conception model of the E+.

operation, checking and corrective action, and management review) according to their interrelationships with which various EM-related information/data can be organized. Because the main task of the EM in construction is to reduce adverse environmental impacts, the dynamic data transference in the framework is the prime focus of the E+. Thus, a conception model of the E+ is illustrated in Figure 2.2.

2.6 Conclusions

The remarkable difference between the rate of ISO 14001 registration and EIA implementation indicates that contractors in mainland China have not really implemented EM and accepted the ISO 14000 series. This hypothesis has been tested in this study by a mail questionnaire survey conducted with contractors in Shanghai. The survey data has been analysed focusing on the ISO 14000 series' acceptability, and the survey results indicate that there are five classes (critical factors) affecting contractors in Shanghai on $ISO\ 14Ks_{A\&I}$. These critical factors include governmental regulations, technology conditions, competitive pressures, cooperative attitude, and cost–benefit efficiency.

Based on the analysis of the ISO 14000 series' acceptability, an empirical evaluation model for deciding on whether to accept the ISO 14000 series has been developed (see Appendix B). The model can be used by contractors to decide whether they should accept the ISO 14000 series in the Shanghai construction industry.

The integrative methodology for EM in construction projects, in which a dynamic EIA process can be effectively and efficiently applied during construction, has been put forward. The implementation of the E+ model requires essential analytical approaches, which belong to the E+ Plan section or E+ Logistics section individually, to carry out data capture and transform stage by stage and realize its conclusive function.

Chapter 3

Effective prevention at pre-construction stage

3.1 Introduction

Environmental issues in construction typically include soil and ground contamination, water pollution, C&D waste, noise and vibration, dust, hazardous emissions and odours, demolition of wildlife and natural features, and archaeological destruction (Coventry and Woolveridge 1999). Since the early 1970s, there have been numerous studies related to environmental issues in construction. Some examples include the study on air pollution (Henderson 1970), noise pollution (U.S.EPA 1971, 1973), water pollution (McCullough and Nicklen 1971), and solid-waste pollution (Spivey 1974a,b) generated from construction sites. On the other hand, although the expression 'EM in construction' was first coined in the *U.S. National Environmental Policy Act* of 1969 (Warren 1973), the embryonic concept of EM in construction was not formulated until the late 1970s, when the role of environmental inspector was introduced in the design and construction phases of projects. The environmental inspector, who plays the role of environmental monitor (Dodds and Sternberger 1992), is a specialist whose academic background or experience results in considerable understanding of environmental impacts and applicable control measures, and acts as an advisor to construction engineers on all matters of EM (Spivey 1974a,b; Henningson 1978). Moreover, enthusiasm for establishing an EMS in a construction company increased quickly following two main important EM standards, BS 7750 (enacted in 1992) and the ISO 14001 EMS (enacted in 1996). The EM standards are regarded as guidance to the construction industry, from passive and one-sided CM on contamination reduction to active and all-round EM.

Pollution and hazards caused by construction projects have become a serious social problem all over the world. The sources of pollution and hazards from construction sites include dust, harmful gases, noises, blazing lights, solid and liquid wastes, ground movements, messy sites, fallen items, etc. These kinds of pollution and hazards can not only annoy residents nearby, but also affect the health and well-being of people in the entire city and area. For example, in big cities in developing countries, such as Shanghai and Beijing in mainland China, air quality has been deteriorating due to extensive and rapid urban redevelopment activities since the 1980s.

To tackle the serious environmental problems partly caused by construction pollution and hazards, environmental laws and regulations are increasingly enacted in different forms in different countries. For example, the Chinese government has issued a number of laws and regulations on environmental protection since the early 1980s. These laws and regulations include *Oceanic Environment Act* (enacted in 1982), *Water Pollution Protection Act* (enacted in 1984), *Air Pollution Protection Act* (enacted in 1987), and *Noise Pollution Protection Act* (enacted in 1989). Especially for the construction industry, the Chinese Ministry of Construction enacted the first *Construction Law* in 1998, which explicitly includes the liabilities and responsibilities of contractors in preventing and reducing the emission of pollutants to the natural environment; and the State Council of China enacted the *Managerial Ordinance on Environmental Protection of Construction Project* in the same year (SC of China 1998), which stipulates that all new construction projects must apply for environmental impact approval following an approval procedure of EIA report/form or EI form before construction. However, investigations by the authors of this book on many conflicts over construction pollution and hazards between construction practice and governmental regulations reveal that contractors need more effective, efficient, and economical EM tools to help them to obey all environmental laws and regulations.

As there are potential requirements of effective, efficient, and economical EM tools in the construction industry, this chapter aims to provide a systematic approach to dealing with environmental pollution potential generated in construction projects at pre-construction stage. The systematic approach comprises the CPI method to evaluate and reduce pollution and hazard levels of construction processes and construction projects, and the env.Plan method to quantitatively evaluate environmental-consciousness of proposed construction plans and thereby select the prime environment-friendly construction plan. This systematic approach allows for both qualitative analysis and control and quantitative assessments through measuring the CPI, and thus the selection of the prime environmental-conscious construction plan through env.Plan decision-making model. The authors believe that the qualitative assessment and control method is useful because it can provide construction project managers with essential knowledge of how to limit environmental pollution to its minimum at pre-construction stage. However, the systematic approach presented here is a necessary complement to EM in construction, as it can be adopted to quantitatively measure the degree of pollution and hazards generated in any particular construction processes and construction projects, then to re-arrange and revise construction plans and schedules in order to reduce the level of pollution and hazards, and thereafter to support decision-making on environmental-conscious construction.

3.2 CPI method

3.2.1 Qualitative analysis of construction pollution

The sources of pollution and hazards generated from construction activities can be divided into seven major types: dust, harmful gases, noise, solid and liquid wastes, fallen objects, ground movements, and others. In order to reduce and prevent these, it is necessary to identify first the construction operations that generate pollution and hazards. In Table 3.1, construction activities that generate pollution and hazards, and corresponding methods for prevention are listed. The contents in Table 3.1 are presented based on an extensive investigation on many construction cases, as well as numerous discussions with many project managers.

Qualitative methods to prevent pollution and hazards are divided into the following four categories:

1 Technology: This category recommends a range of advanced construction technologies which can reduce the amount of dust, harmful gases, noise, solid and liquid wastes, fallen objects, ground movements, and others. For example, replacing the impact hammer pile driver with the hydraulic piling machine can significantly reduce the level of noise generated by the piling operation.
2 Management: This category recommends the use of modern CM methods which may help reduce the amount of dust, noise, solid and liquid wastes, fallen objects, and others.
3 Planning: This category emphasizes revising and re-arranging construction schedules to reduce the aggregation of pollution and hazards. This category has effect on dust, noise, solid and liquid wastes, fallen objects, ground movements, and others.
4 Building material: Better building material can also help reduce pollution and hazards. This category has effect on harmful gases, fallen objects, ground movements, and others.

These four categories of preventive methods and their effects are also summarized in Table 3.2 (Chen, Li and Wong 2000).

The authors believe that it is possible to effectively control and reduce the amount of pollution and hazards in some respects by adopting these preventive methods. However, one limitation of the qualitative methods is their incapability towards quantifying and adjusting pollution and hazards of a construction procedure initiatively. In order to further quantitatively analyse the level of pollution and hazards, the next section describes a method to quantify and re-distribute pollution and hazards, generated from construction processes and construction projects, below legal limits.

Table 3.1 Causes of pollution and hazards and preventive methods

Type	*Causes*	*Methods to prevent*
Dust	Demolition, rock blast	Static crushing/chemical breaking/water jet
	Excavation, rock drilling	Static crushing/chemical breaking/wet excavation/wet drilling
	Open-air rock power and soil	Covering/wet construction
	Open-air site and structure	Wet keeping/site clearing/mask
	Bulk material transportation	Awning/concrete goods/washing transporting equipment
	Bulk material loading and unloading	Concrete goods/packing and awning/wet keeping
	Open-air material	Awning/storehouse
	Transportation equipment	Cleaning
	Concrete and mortar making	Concrete goods
Harmful gases	Construction machine – pile driver	Hydraulic piling equipment
	Construction machine – crane	Electric machine
	Construction machine – electric welder	Bolt connection/pressure connection
	Construction machine – transport equipment	Night shift
	Construction machine – scraper	Electric machine
	Organic solvent	Poison-free solvent
	Electric welding	Bolt connection/pressure connection
	Cutting	Laser cutting
Noise	Demolition	Static crushing/chemical breaking
	Construction machine – pile driver	Hydraulic pile equipment
	Construction machine – Crane	Electric machine
	Construction machine – rock drill	Static crushing/chemical breaking
	Construction machine – mixing machinery	Concrete goods/prefabricated component
	Construction machine – cutting machine	Laser cutting machine/ prefabrication/soundproof room/wall
	Construction machine – transport equipment	Night shift (based on the location of construction site)
	Construction machine – scraper	Night shift (based on the location of construction site)

Table 3.1 (Continued)

Type	*Causes*	*Methods to prevent*
Ground movements	Demolition	Static crushing/chemical breaking
	Pile driving	Static pressing-in pile
	Forced ramming	Static compacting/limited using
Wastes	Solid-state waste – building material waste	Prefabricated component/ recovery
	Solid-state waste – building material package	Recovery
	Liquid waste – mud/building material waste	Recovery
	Liquid waste – machinery oil	Material saving
Fallen objects	Solid-state waste – building material waste	Material optimum seeking/ technology improving
	Solid-state waste – building material package	Recovery
	Liquid waste – mud/Building material waste	Technology improving/recovery
	Liquid waste – construction water	Recovery
	Construction tools – scaffold and board	Safety control/reliable tools
	Construction tools – model plate	Technology improving/safety control
	Construction tools – building material	Technology improving/recovery
	Construction tools – sling/others	Safety control
Others	Urban transportation – road encroachment	Enclosing wall/night shift/ underground construction
	Civic safety – demolition	Static crushing/chemical breaking
	Civic safety – automobile transportation	Overloading forbidden/speed limiting
	Civic safety – tower crane	Safety control
	Civic safety – construction elevator	Safety control
	Civic safety – foundation/earth dam	Safety control
	Urban landscape – structure exposed	Masking
	Urban landscape – night lighting	Using projection lamp
	Urban landscape – electric-arc light	Bolt connection/pressure connection/prefabricated component
	Urban landscape – mud/waste water	Drainage organization
	Urban landscape – civic facility destruction	Technology improving/plan preconception

Table 3.2 Countermeasures for construction pollution and their effects

Category	*Pollution and hazards*						
	Dust	*Harmful gases*	*Noise*	*Ground movements*	*Wastes*	*Fallen objects*	*Others*
Technology	√	√	√	√	√	√	√
Management	√	x	√	x	√	√	√
Planning	√	x	√	x	o	x	√
Material	x	√	x	o	x	x	o

Notes
√ – More effective; o – Partial effective; x – Ineffective.

3.2.2 *Construction pollution measurement*

3.2.2.1 *Pollution control in construction projects*

Pollution control in construction projects can be defined as the control of all human activities that have either a significant or small negative impact on both natural and social environments during the entire construction process. It is an essential part of the implementation of EM in any individual construction project (Griffith *et al.* 2000). Construction pollution has been given great attention in the industry since the 1970s, not only in academic research but also in professional practice. From ASCE (www.asce.org), ICE (www.ice.org.uk), and EI (www.ei.org) online databases, the authors found that noise pollution inconstruction was first identified in a professional research in the early 1970s (U.S.EPA 1971), followed by air pollution (Jones 1973) solid-waste pollution (Skoyles and Hussey 1974; Spivey 1974a,b), and so forth. The concept of EM during construction was put forward in the late 1970s, and the role of environmental inspector, represented by a CM engineer, was introduced in the design and construction phases of projects. From then on, researches, worldwide, focused on the quantitative measurement and effective control approaches to reducing pollution and hazards, such as life-cycle costing; efficient energy consumption; reduction, re-use, and recycle of C&D material/debris; degradation and abatement of construction noise and dust; EIA, etc. Even so, there was little enthusiasm to establish an EMS in a commercial construction company until two main important standards, BS 7750 (1992) and the ISO 14001 EMS (1996), were promulgated. As the EMS is an organization's formal structure that implements EM (Griffith *et al.* 2000), approaches to construction pollution control are useful and effective in all environment-friendly practices in construction projects.

3.2.2.2 *Construction pollution index*

In many cases, conflicts between construction practice and governmental regulations arose regarding the permissible level of polluting emission, especially if the construction sites are in densely polluted areas. For example, the *Noise Pollution Protection Act* (NPPA 1993) in China specifies that the level of noise should not exceed 75 dB(A), above which site operations will be suspended by legal actions. In a construction site, the level of pollution emission from individual operations may not exceed the legal limits specified under the regulations; however, the aggregated level of pollution from multiple sources may exceed the limit. To prevent this and to ensure that the level of polluting emission does not exceed the legal limits during construction, a two-step quantitative method, as described in this section, can be followed. First, the method can predict the distribution of polluting-emission levels throughout a project's duration. Second, if it detects that the level of pollution exceeds the limit at a certain point of time, then on-site activities are re-scheduled so that the level of pollution can be re-distributed.

As a construction project generally spans over a year or even longer, the method of quantitative analysis should involve continuous monitoring and assessment for the entire project duration. CPI in measured as shown in Equation 3.1.

$$\mathrm{CPI} = \sum_{i=1}^{n} \mathrm{CPI}_i = \sum_{i=1}^{n} h_i \times D_i \tag{3.1}$$

where CPI is the construction pollution index of an urban construction project, CPI_i is the CPI of a specific construction operation i, h_i is the pollution and hazard magnitude per unit of time generated by a specific construction operation i, D_i is the duration of the construction operation i that generates pollution and hazards h_i, and n is the number of construction operations that generate pollution and hazards.

In Equation 3.1, parameter h_i is a relative variable, and its value is in the range of [0, 1]. If $h_i = 1$, it means that the pollution and hazards can cause fatal damage or catastrophes to people and properties nearby. For example, if a construction operation generates some noise and the sound level at the receiving end exceeds the "threshold of pain", which is 140 dB(A) (McMullan 1998), then the value of h_i for this specific construction operation is 1. If $h_i = 0$, then it indicates that no pollution and hazards are detectable from a construction operation.

The initial value of each h_i depends on experience and expert opinions and can be taken as the average of scores from experts. However, this calculation method cannot give an accurate value to each h_i because the average may not be a real value of the h_i or provide a most appropriate value to each h_i. To overcome this drawback in Equation 3.1, and to extend this quantitative pollution measurement approach from construction pollution indication to general P3 in construction and demolition projects, the authors developed an alternative index, i.e. stochastic process pollution index (SPPI) based on Equation 3.1. And it can be measured by Equations 3.2 and 3.3.

$$SPPI = \sum_{i=1}^{n} SPPI_i = \sum_{i=1}^{n} h_i \times D_i \tag{3.2}$$

$$h_i = \frac{h_i^{(\mathrm{optimistic})} + 4 \times h_i^{(\mathrm{mostlikely})} + h_i^{(\mathrm{pessimistic})}}{6} \tag{3.3}$$

where *SPPI* is the stochastic process pollution index of a project, $SPPI_i$ is the *SPPI* of a specific process i, h_i is the expected hazard magnitude per unit of time generated by a specific process i, $h_i^{(optimistic)}$ is the optimistic hazard magnitude per unit of time generated by a specific process i, $h_i^{(mostlikely)}$ is the most likely hazard magnitude per unit of time generated by a specific process i, $h_i^{(pessimistic)}$ is the pessimistic hazard magnitude per unit of time generated by a specific process i, D_i is the duration of the specific process i that generates pollution and/or hazard h_i, n is the number of processes that generate pollution and hazards.

Equations 3.2 and 3.3 provide an innovative way to define h_i. The SPPI assumes a beta probability distribution for the h_i estimates. Regarding each h_i, each expert will provide a set of values – $h_i^{(optimistic)}$, $h_i^{(mostlikely)}$, and $h_i^{(pessimistic)}$ – from which the expected h_i is calculated by their weighted average. Comparing with the programme evaluation and review technique (PERT) adopted in project scheduling, the approximate treatment gives a more reasonable result for each h_i.

It is then possible to identify values of h_i for all types of pollution and hazards generated by commonly used construction operations. For example, according to the information on sound emission from piling machines, as well as the types of piles, the authors derive the values of h_i for some piling operations (Table 3.3).

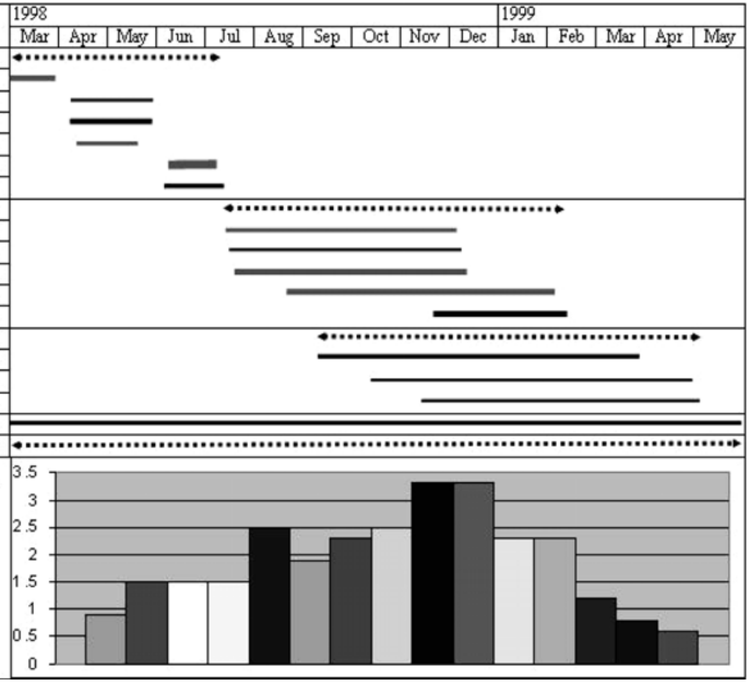
Data such as those regarding the emissions of noise, harmful gases, and wastes are normally available in the product specifications of construction machinery and equipment, or can be conveniently measured. These data can then be converted to h_i value by normalizing them into the range of [0, 1]. In case there is no data available for such conversion, h_i values have to be decided based on the user's experience and expert opinions.

It is also very useful to create a CPI bar chart. The CPI bar chart is very similar to the ordinary bar charts used in construction scheduling, except that the thickness of the bars in the histogram represents the h_i value for the corresponding construction operation. By integrating the concept of CPI method into Microsoft Project©, which is a commonly used tool in construction project management, the authors think it is possible to develop a system to neatly combine EM with project management, as shown in Figure 3.1.

Table 3.3 Values of h_i for some piling operations

Number	*Piling operations*	*h_i value (per day)*
1	Prefabricated concrete piles using drop-hammer driver	0.5
2	Sheet steel piles using drop-hammer driver	0.6
3	Prefabricated concrete piles using hydraulic piling driver	0.2
4	Sheet steel piles using hydraulic piling driver	0.3
5	Bored piling	0.1
6	Sheet steel piles using drop-hammer driver	0.7
7	Prefabricated concrete piles using static pressing-in driver	0.2

ID	Task Name	h_t Value	Duration (days)	Start	Finish
	Foundation Work		136	03/01/98	07/15/98
1	Prefabricated Concrete Piles Using Drop-hammer	0.5	31	03/01/98	04/01/98
2	Steel Sheet Piles Using Hydraulic Piling Driver	0.2	57	04/05/98	06/01/98
3	Earthwork-Transportation	0.6	57	04/05/98	06/01/98
4	Support System-Building	0.3	42	04/08/98	05/20/98
5	Support System-Demolition	0.7	28	06/10/98	07/08/98
6	Foundation Construction	0.4	43	06/02/98	07/15/98
	Carcass Work		219	07/16/98	02/20/99
7	RC Work-Rebar	0.3	155	07/16/98	12/18/98
8	RC Work-Form	0.2	155	07/18/98	12/20/98
9	RC Work-Concrete	0.5	156	07/19/98	12/22/98
10	Masonry Work	0.5	176	08/18/98	02/10/99
11	Structural Steelwork	0.6	94	11/18/98	02/20/99
	Finish Work		242	09/01/98	05/01/99
12	Wall	0.4	211	09/01/98	03/31/99
13	Ceiling	0.2	211	10/01/98	04/30/99
14	Floor	0.2	181	11/01/98	05/01/99
15	**Transportation Work**	0.4	435	03/01/98	05/10/99
	Total Construction Period		435	03/01/98	05/10/99



NOTE:
Height of the bars represents the h_1 value of the corresponding construction operation.

Figure 3.1 Project scheduling together with EM using CPI.

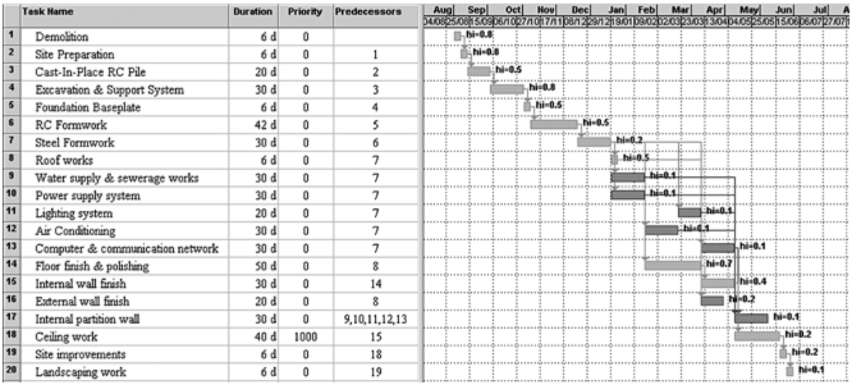
In Figure 3.1, the h_i values are listed next to the task name of their corresponding construction operations. As the height of the bar represents the h_i value, the area of the bar represents the CPI value of the corresponding construction operation. For example, the sample construction project (refer to Figure 3.1) involves a piling operation which includes the following activities and durations (measured in number of days):

- Driving prefabricated concrete piles using drop-hammer driver, and duration is 31 days.
- Driving sheet steel piles using hydraulic piling driver, and duration is 57 days.

Then, according to Equation 3.1, the value of CPI for the piling operation is $0.5 \times 31 + 0.3 \times 57 = 32.6$, and the overall CPI value for the project is 747.2. The value of CPI reflects the accumulated amount of pollution and hazards generated by a construction project within its project duration. That is the aggregation of the thickness of histograms, as indicated at the bottom of the bar chart (see Figure 3.1), represents the distribution of the CPI value along the whole project duration. This distribution is particularly useful for project managers to identify the periods when the project will generate the highest amount of pollution and hazards. Therefore, preventive methods such as those listed in Table 3.1 can be applied to reduce the amount of pollution and hazards during those periods.

Careful study of the sample project revealed that during November–December 1998 the project generated the highest pollution and hazard level according to the distribution diagram of Figure 3.1, and the root of the pollution is the large amount of on-site mixing of concrete and masonry work during that period. The project manager foresaw the problem, and decided to reduce the amount of on-site mixing of concrete in those months by using 25% ready-mixed concrete. As a result, the amount of noise generated from on-site concrete mixing was reduced. The h_i value decreased in November–December 1998 from 3.3 to 2.5, a 25% reduction in the value of $h_{i.}$ It also indicates that the total amount of pollution and hazards is consequently reduced.

Figure 3.2 illustrates another example of a construction project comprising 20 activities. The h_i value of each activity is presented in Table 3.4 and indicated at the right side of the bars in Figure 3.2. For example, the h_i value for “RC Formwork” is calculated to be 0.5. Moreover, the y-axis in Figure 3.3 represents the accumulated h_i value and the x-axis is for the project duration. Thus, the shaded area is the total CPI value. It is suggested that the maximum permissible level of h_i is 0.8 at any point of time during construction. It is necessary to note that the definition of maximum level of h_i value is based on the average allowable pollution and hazard level. The value of maximum h_i can be adjusted to reflect the level of pollution and hazard control: the lower the maximum h_i value, the tighter the control on pollution and hazards, and vice versa.



	Task Name	Duration	Priority	Predecessors
1	Demolition	6 d	0	
2	Site Preparation	6 d	0	1
3	Cast-In-Place RC Pile	20 d	0	2
4	Excavation & Support System	30 d	0	3
5	Foundation Baseplate	6 d	0	4
6	RC Formwork	42 d	0	5
7	Steel Formwork	30 d	0	6
8	Roof works	6 d	0	7
9	Water supply & sewerage works	30 d	0	7
10	Power supply system	30 d	0	7
11	Lighting system	20 d	0	7
12	Air Conditioning	30 d	0	7
13	Computer & communication network	30 d	0	7
14	Floor finish & polishing	50 d	0	8
15	Internal wall finish	30 d	0	14
16	External wall finish	20 d	0	8
17	Internal partition wall	30 d	0	9,10,11,12,13
18	Ceiling work	40 d	1000	15
19	Site improvements	6 d	0	18
20	Landscaping work	6 d	0	19

Figure 3.2 Initial schedule of a construction project.

Table 3.4 h_i values of some construction operations

Task name	*h_i Value (per day)*
Demolition	0.7
Site preparation	0.7
Cast-in-place RC Pile	0.5
Excavation and support system	0.7
Foundation baseplate	0.3
RC framework	0.5
Steel framework	0.2
Roof works	0.5
Water supply and sewerage works	0.1
Power supply system	0.1
Lighting system	0.1
Air conditioning	0.1
Computer and communication network	0.1
Floor finish and polishing	0.7
Internal wall finish	0.4
External wall finish	0.2
Internal partition wall	0.1
Ceiling work	0.2
Site improvements	0.2
Landscaping work	0.1

It is also necessary to note the CPI histogram is produced by linearly accumulating h_i values. This may cause inaccuracies as some pollution measurements such as noise levels cannot be linearly added up. The authors are examining, at the time of writing, the effect of nonlinearity and are aiming to develop a revised method to accumulate h_i values so that accurate histograms

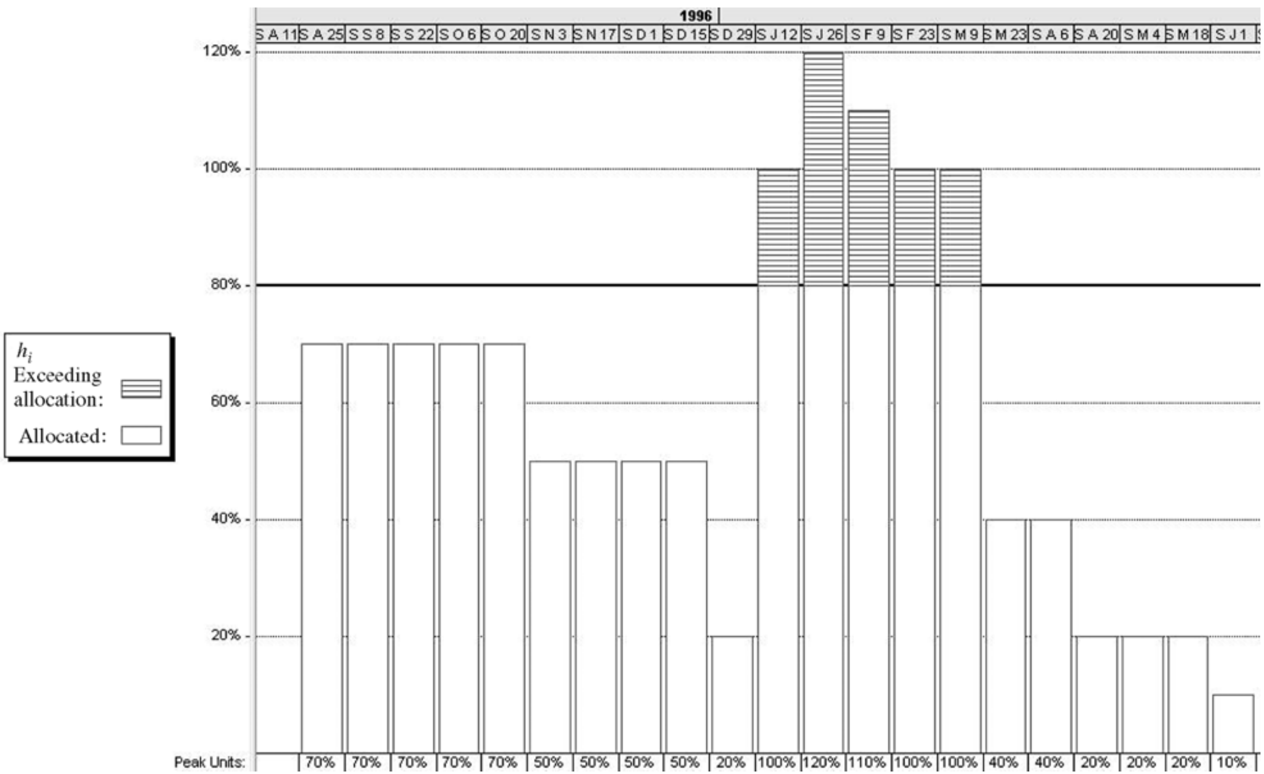


Figure 3.3 Histogram of h_i in the initial schedule.

can be produced. However, it can be seen from Figure 3.2 that during the period December 1996 to March 1997 of the project duration, the level of h_i values will exceed the maximum value, indicating that during this period, the accumulated level of pollution will exceed the limit. Therefore, it is necessary to re-arrange the project schedule so that the level of pollution can be reduced below the limit.

3.2.3 A pseudo-resource approach for CPI levelling

Resource levelling can smooth daily resource demands, and it is an effective tool for construction project scheduling when construction resource conflicts or shortages occur. This section presents a method to combine pollution and hazard control with traditional construction resource levelling at project scheduling stage. The h_i values are treated as a pseudo resource, and the maximum h_i value is treated as the limit of the pseudo resource. This pseudo resource together with other types of resources can be levelled by using the traditional construction resource levelling methods (Pilcher 1992).

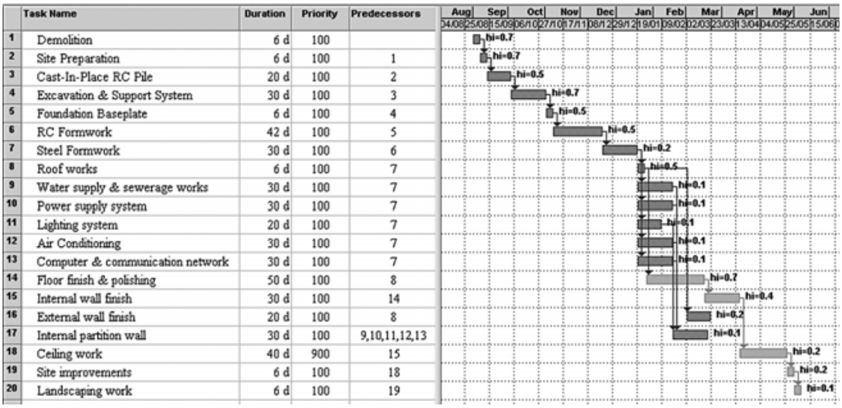
In the experimental project schedule, which is described in Figures 3.2 and 3.3, the authors found that if they set h_i as a kind of pseudo resource, then construction pollution and hazards can be levelled following resource levelling. Although there would be different construction pollution emissions depending on the different daily resources demanded in a schedule, it is still possible to adjust the level of construction pollution with the help of h_i. As h_i is a measurement relative to all other real resources such as materials and workers in a schedule, it can be integrated with resource optimization.

In the sample project considered, there are six kinds of construction resources – workers, materials, machines, instruments, and power (denoted as R_1, R_2, R_3, R_4, and R_5); and pollution and hazards from construction are treated as a pseudo resource, which is denoted as R_6. These resources are listed in Table 3.5. For the purpose of convenience in calculation, the values of the resources are adjusted so that there will be no very large or small figures.

In order to test the pseudo-resource approach, the authors chose Microsoft Project© as a tool for scheduling and resource levelling. The project schedules

Table 3.5 Resources in initial construction schedule

Resource name	*Mark*	*Max units available*	*Adjustment*
Workers	R_1	1900	Workers no. × 10
Materials	R_2	2200	Materials cost × 0.01
Machines	R_3	2100	Machines cost × 0.01
Instruments	R_4	3100	Instruments cost × 0.01
Power	R_5	3400	Power cost × 0.01
h_i	R_6	80	CPI × 100



	Task Name	Duration	Priority	Predecessors
1	Demolition	6 d	100	
2	Site Preparation	6 d	100	1
3	Cast-In-Place RC Pile	20 d	100	2
4	Excavation & Support System	30 d	100	3
5	Foundation Baseplate	6 d	100	4
6	RC Formwork	42 d	100	5
7	Steel Formwork	30 d	100	6
8	Roof works	6 d	100	7
9	Water supply & sewerage works	30 d	100	7
10	Power supply system	30 d	100	7
11	Lighting system	20 d	100	7
12	Air Conditioning	30 d	100	7
13	Computer & communication network	30 d	100	7
14	Floor finish & polishing	50 d	100	8
15	Internal wall finish	30 d	100	14
16	External wall finish	20 d	100	8
17	Internal partition wall	30 d	100	9,10,11,12,13
18	Ceiling work	40 d	900	15
19	Site improvements	6 d	100	18
20	Landscaping work	6 d	100	19

Figure 3.4 Microsoft Project©-levelled project schedule.

levelled by Microsoft Project© and the corresponding histogram of h_i values are illustrated in Figures 3.4 and 3.5, respectively. From Figures 3.4 and 3.5, we find that the construction pollution level spreads out under the line of the maximum permissible level of h_i (maximum $h_i = 0.8$) when the other five resources (refer to Table 3.5) are also levelled down to their individual resource limits. Therefore, the pseudo-resource approach for reducing construction pollution and hazard level is feasible at project scheduling stage. However, the total construction period is stretched by 22 days in Figure 3.4 after resource levelling. It is about 8% longer than the original schedule in Figure 3.2. Similar results were obtained from additional experimental schedules, which are not presented in this book. The experimental research therefore revealed that the pseudo-resource approach can assist project managers to keep construction pollution and hazard level below a legal range while making little difference to their normal schedules. The results from the experiment also indicated that it is necessary to find an optimum method to arrive at a shorter schedule for the proposed construction project with every resource levelled, including the pseudo resource.

3.2.4 CPI levelling using GA

A comparative analysis of resource-levelling and resource-allocation capabilities of project management software packages indicates that heuristic methods have a better performance than Microsoft Project© and Primavera Project Planner (Farid and Manoharan 1996). In recent years, research on construction schedule has improved the theory of resource levelling and allocation with heuristic techniques (Reeves 1993) considerably. For example, an artificial neural network (ANN) is used to minimize project duration and cost by using a mathematical model based

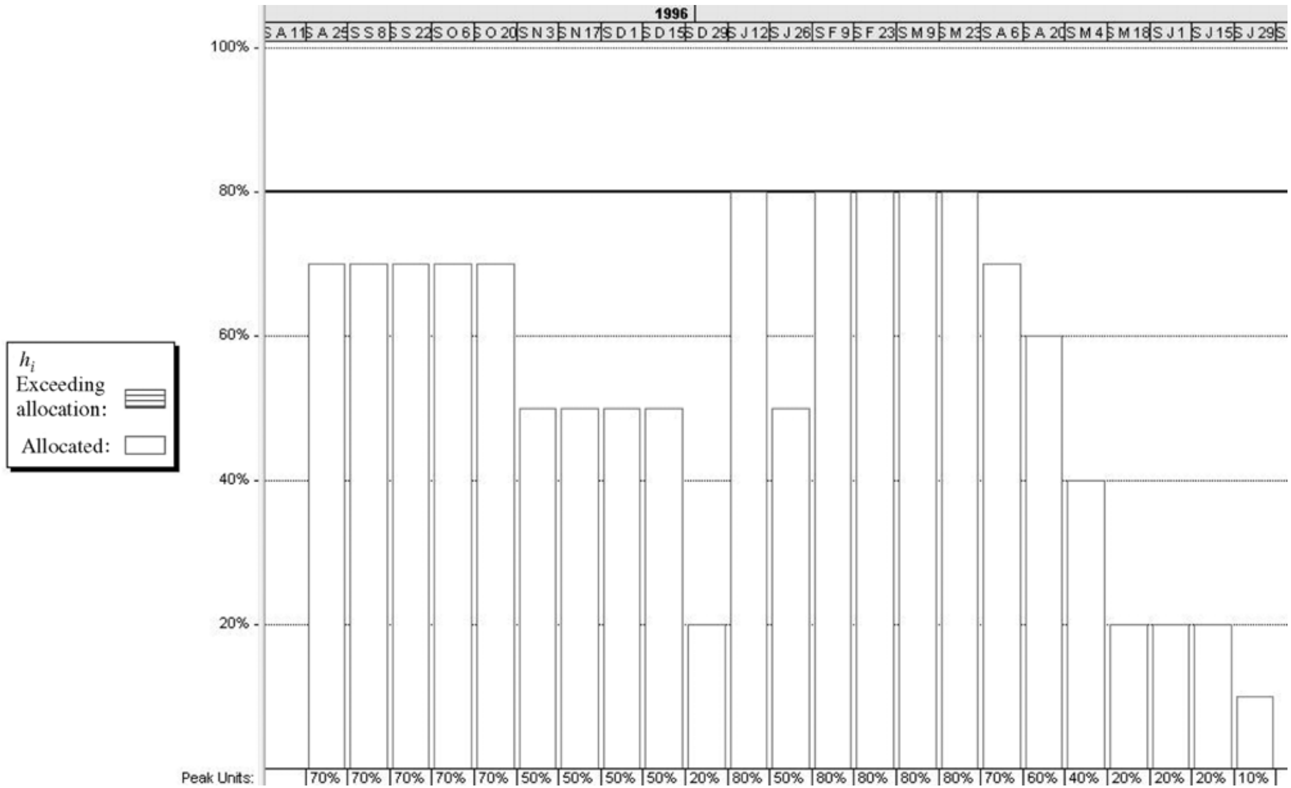


Figure 3.5 Histogram of h_i values associated with the schedule levelled by Microsoft Project©.

on precedence relationships, multiple crew-strategies, and time–cost trade-off (Adeli and Karim 2001; Senouci and Adeli 2001), and GA is used to search for a near-optimum solution to the problem of resource allocation and levelling integrated with time–cost trade-off model, resource-limited/constrained model, and resource levelling model (Chan *et al.* 1996; Chua *et al.* 1996; Li and Love 1997; Li, Cao, and Love, 1999; Hegazy 1999; Leu and Yang 1999; Leu *et al.* 1999). To integrate various heuristic methods into resource levelling, the methods used by Harris (1978) and Hegazy (1999), which minimize both daily fluctuations in resource use and the resource utilization period, have been adapted. According to Hegazy (1999), the moment of fluctuations in daily resource use can be calculated using Equation 3.4.

$$M_{\mathrm{x}}^{\mathrm{R}} = \sum_{j=1}^{n} RP_j^2 \tag{3.4}$$

And the moment for measuring the resource utilization period is calculated using Equation 3.5.

$$M_{\mathrm{y}}^{\mathrm{R}} = \sum_{j=k}^{n} (j-k) RP_j \tag{3.5}$$

These two moment calculations can be used in minimizing either resource fluctuations or the duration of resource use, or both. As concurrent optimization of resource levelling and pollution and hazard control is a nonlinear searching problem, GA is suitable to solve it.

3.2.4.1 Gene formation

In a number of commercial resource levelling software packages, the user is allowed to set priority levels to tasks. Priority is an indication of a task's importance and availability for levelling (that is, resolving resource conflicts or over-allocations by delaying or splitting certain tasks). The task priority setting controls levelling, which allows users to control the order in which software systems such as Microsoft Project© can delay tasks with over-allocated resources. Tasks with the lowest priority are delayed or split first, and tasks with a higher priority are not levelled before other tasks sharing the over-allocated resources. A previous comparison of heuristic and optimum solutions in resource-constrained project scheduling shows activity priority to be a key factor of a heuristic rule. The heuristic rule which bases activity priority on activity slack produced an optimal schedule span most and exhibited the lowest average increase above optimum of the heuristic rules examined (Davis and Patterson 1975). A heuristic fuzzy expert system has also proved that priority ranking can obtain an optimum result in construction resource scheduling (Chang *et al.* 1990). Thus, to apply GA to solve the multiple-resources levelling problem, it is essential to have a

1	2	3	4	5	6	7	8	9		j
P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	...	P_j

Notes

1. P_j is the priority of active j, $0 \le P_j \le 8$.
   $P_j = 0$, activity priority is highest;
   $P_j = 1$, activity priority is higher;
   $P_j = 2$, activity priority is very high;
   $P_j = 3$, activity priority is high;
   $P_j = 4$, activity priority is medium;
   $P_j = 5$, activity priority is low;
   $P_j = 6$, activity priority is very low;
   $P_j = 7$, activity priority is lower;
   $P_j = 8$, activity priority is lowest.
2. The priority values are in accordance with the priority grades of actives in Microsoft Project®.

Figure 3.6 Gene formation (Hegazy 1999).

gene structure that facilitates the operations of GA. Bearing this in mind, the following gene format used by Syswerda and Palmucci (1991), Grobler *et al.* (1995), Boggess and Abdul (1997), and Hegazy (1999) has been adopted:

In Figure 3.6, a string has j genes, and each box represents a gene. The number inside the box is the priority setting for a particular task labelled by the number above the box. A string is a particular combination of priority settings that determines a specific schedule. The fitness of the string is evaluated by the following function (Hegazy 1999),

$$\omega_{\mathrm{d}}(D_i/D_0) + \sum_{j=1}^{n} [\omega_j^{\mathrm{R}}(M_{\mathrm{x}ji}^{\mathrm{R}} + M_{\mathrm{y}ji}^{\mathrm{R}})/(M_{\mathrm{x}j0}^{\mathrm{R}} + M_{\mathrm{y}j0}^{\mathrm{R}})] \tag{3.6}$$

where $M_{\mathrm{x}}^{\mathrm{R}}$ is the moment of fluctuations of daily resource use as defined in (3.4); $M_{\mathrm{x}ji}^{\mathrm{R}}$ is the moment of fluctuations of resource use in a specific schedule determined by string i in day j; $M_{\mathrm{x}j0}^{\mathrm{R}}$ is the initial value of $M_{\mathrm{x}}^{\mathrm{R}}$ in day j; $M_{\mathrm{y}}^{\mathrm{R}}$ is the moment of resource utilization period, as defined in (3.5); $M_{\mathrm{y}ji}^{\mathrm{R}}$ is the moment of resource utilization period of a schedule determined by a string i in day j; $M_{\mathrm{y}j0}^{\mathrm{R}}$ is the initial value of $M_{\mathrm{y}}^{\mathrm{R}}$ in day j; D_i is the new project duration of the schedule determined by string i; D_0 is the initial project duration determined by any resource allocation heuristic rule; ω_{d} is the weight in minimizing project duration; ω_j^{R} is the weight in levelling every resource in day j; i is the generation number of genes; j is the representative day during a project's total working days, and n is the number of working days in a project's duration.

By selecting different weights, the fitness function (3.6) enables the user to conduct different heuristics-based resource levelling including reducing resource fluctuations, minimizing the duration of resource use, or both.

3.2.4.2 Experimental results

This section presents experimental results obtained by using GA to combine pollution control and resource allocation into the task of resource levelling. The schedule used in the experiment is that of a construction project in Shanghai, in which there are 20 activities for general control, and the initial schedule of the activities and their associated level of polluting emission (h_i value) are shown in Figure 3.2. From the histogram of h_i values, which is illustrated in Figure 3.3, it can be seen that the accumulated level of polluting emission exceeds the permissible limit.

In the experiment, the initial population size is set at 100. Also, to minimize both resource fluctuations and duration, the weightings in the fitness function (3.6) are given an equal weighting of 1. The resultant schedule and the associated histogram of h_i values are illustrated in Figures 3.7 and 3.8.

Comparing the GA-levelled schedule with the Microsoft Project©-levelled schedule, it can be seen that the priorities of resource use in the GA levelled schedule are set at different values (Figure 3.7); whereas priorities in the Microsoft Project©-levelled schedule (Figure 3.4) do not have any changes from the original schedule (Figure 3.2). In addition, the duration of the GA-levelled schedule is 298 days, which is shorter than the duration of the schedule levelled by Microsoft Project© (302 days). Moreover, two additional experiments conducted by the authors also support these facts. From the experiments, the authors conclude that the GA can adjust the task priorities for the re-distribution of resources to meet resources constraints and make the schedule shorter; moreover, the GA enhances the levelling function of Microsoft Project©, as it enables the user to identify the optimal settings of task priorities in resource levelling automatically.

	Task Name	Duration	Priority	Predecessors
1	Demolition	6 d	100	
2	Site Preparation	6 d	100	1
3	Cast-In-Place RC Pile	20 d	100	2
4	Excavation & Support System	30 d	100	3
5	Foundation Baseplate	6 d	100	4
6	RC Formwork	42 d	100	5
7	Steel Formwork	30 d	100	6
8	Roof works	6 d	100	7
9	Water supply & sewerage works	30 d	100	7
10	Power supply system	30 d	100	7
11	Lighting system	20 d	100	7
12	Air Conditioning	30 d	100	7
13	Computer & communication network	30 d	100	7
14	Floor finish & polishing	50 d	100	8
15	Internal wall finish	30 d	100	14
16	External wall finish	20 d	100	8
17	Internal partition wall	30 d	100	9,10,11,12,13
18	Ceiling work	40 d	900	15
19	Site improvements	6 d	100	18
20	Landscaping work	6 d	100	19

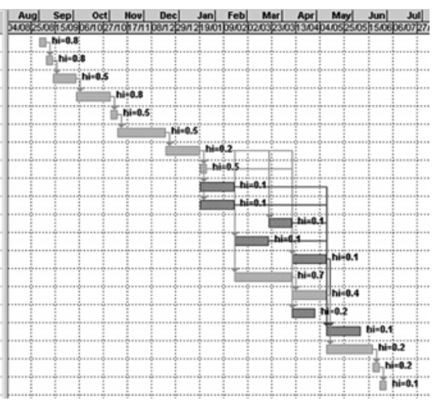


Figure 3.7 GA-optimized construction schedule.

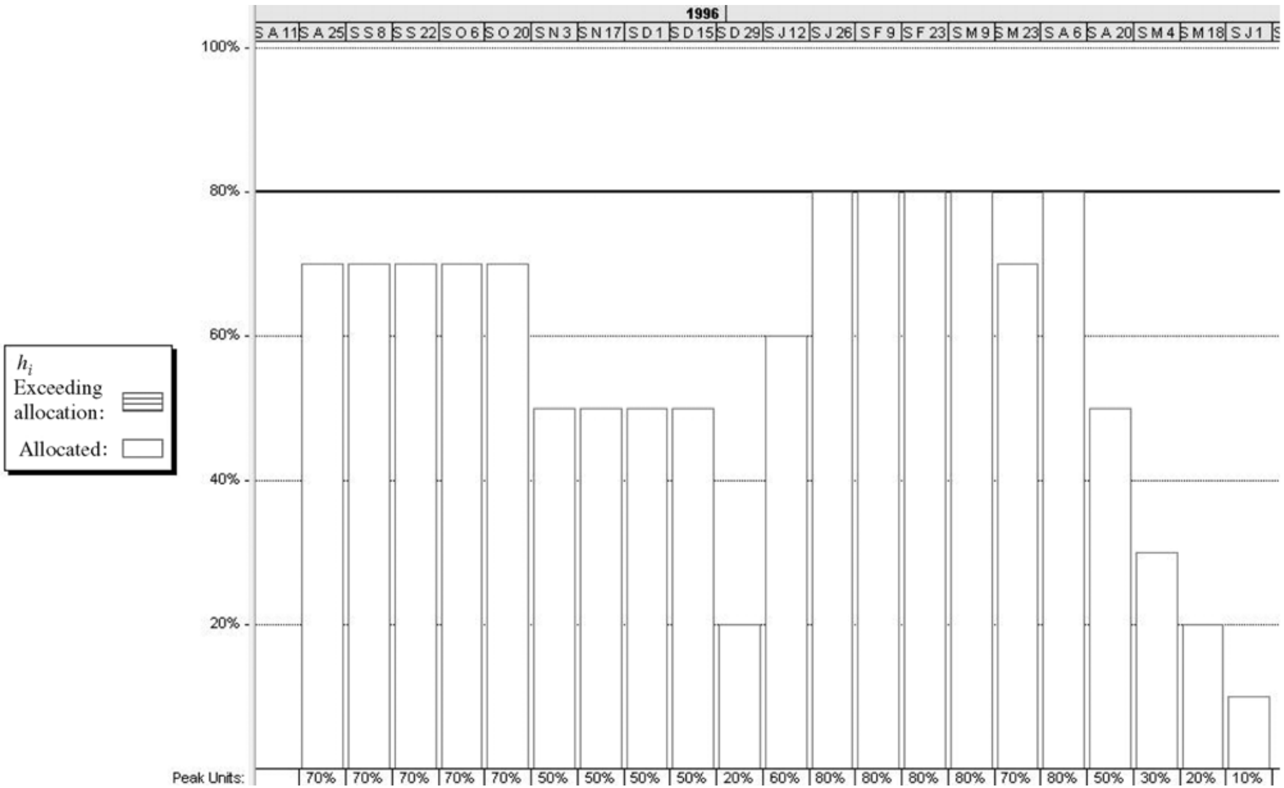


Figure 3.8 Histogram of h_i values associated with the schedule levelled by GA.

3.3 Env.Plan method

3.3.1 Introduction

Although the CPI method has demonstrated its effectiveness and usefulness in indicating, reducing, or mitigating pollution and hazard level during construction planning stage (Chen *et al.* 2000; Li *et al.* 2002), the problem of how to select the best construction plan based on levelling the magnitude of quantified adverse environmental impacts of construction operations is still a research task. Moreover, the major premise of CPI's application in construction plan evaluation is that each construction activity's CPI can be linearly aggregated, and this hypothesis cannot directly reflect the complicated nonlinear causal relationship among construction activities that have environmental impact. In this section, the authors introduce the use of ANP to develop a decision support model named env.Plan. This method aims to integrate important considerations of construction planning, which includes time, cost, quality, and safety, with the evaluation of the impact of various environmental factors, so that the most suitable plan can be obtained.

A construction plan is normally evaluated through fixed criteria such as cost, time, quality, safety, and so on during the planning period. Since effective planning has considerable influence on the successful completion of a construction project, both construction managers and researchers are aware of tools used to prepare and evaluate a construction plan. The analytic hierarchy process (AHP), which is known as a powerful and flexible decision-making process to help people set priorities and make the best decision when both qualitative and quantitative aspects of a decision need to be considered, has been utilized in various areas of construction research and practice since the late 1970s (Zeeger and Rizenbergs 1979), including construction planning (Dey *et al.* 1996). In this regard, the AHP method is recommended by construction researchers as a useful multicriteria assessment tool for its stronger mathematical foundation, its ability to gauge consistency of judgements, and its flexibility in the choice of ranges at the subcriteria level (Khasnabis *et al.* 2002).

However, a notable weakness of AHP is that it cannot deal with interconnections between decision factors in the same level, because an AHP model is structured in a hierarchy in which no horizontal links are allowed. In fact, this weakness can be overcome by using a senior multicriteria analytical technique known as ANP. The ANP is more powerful in modelling complex decision environments than the AHP because it can be used to model very sophisticated decisions involving a variety of interactions and dependencies (Meade and Sarkis 1999; Saaty 1999). These advantages are embodied in several examples of applications of the ANP (Srisoepardani 1996). For example, Saaty (1996) recommended the ANP to be used in cases where the most thorough and systematic analysis of influences needs to be made. In addition, the ANP method has been successfully applied to the strategic evaluations of environmental practices and programmes in both manufacturing and business to help analyse various project-, technological- or business-decision alternatives, and it also has been proved to be useful for modelling dynamic strategies and systemic influences on managerial decisions related to the EM (Meade and Sarkis 1999). As a result, the ANP is selected.

3.3.2 Environmental indicators

In order to find suitable environmental indicators to evaluate a construction plan, the authors conducted an extensive literature review according to a classification of environmental indicators. The literature review on environmental issues in construction was conducted in several dominant databases. These are the Civil Engineering Database (CEDB) of the American Society of Civil Engineers (ASCE), the Compendex® database of the Engineering Index (EI), the Engineering News-Record (ENR) executive search engine (enr.com) and magazines of the McGraw-Hill Companies, the Construction Plus (CN+) search engine (www.cnplus.co.uk) of the Emap Construction Network, and the advanced search engine of the U.S. Environmental Protection Agency (U.S.EPA) (www.epa.gov). In addition to these five dominant databases, a commonly used search engine, Google (www.google.com), was also employed to search for online literature. The search results contained thousands of articles and reports related to environmental impacts and EM in construction practice.

A summary of literature retrieved is listed in Table 3.6. This included 367 references in the ASCE's CEDB and 908 references in the EI's Compendex®, which are relevant to environment-friendly technology, management, and material.

Environmental indicators here refer to factors in a construction project that can adversely or favourably impact on the natural environment and can directly influence construction planning. Based on this, environmental factors can be grouped into adverse environmental factors (denoted as EA factors) and favourable environmental factors (denoted as EF factors). The third category of indicators is those that may lead to adverse or favourable environmental impact depending on the specific environmental conditions in which a construction project is executed. This category of environmental indicators is named as uncertain environmental indicators, or EU factors.

Following the classification described above, a procedure for identifying environmental indicators is illustrated in Figure 3.9. It indicates that the environmental indicators were identified based on an extensive literature review of databases and online materials. The environmental indicators are interrelated with technology, resource, time, cost, management, society, and the natural environment in which a construction project is executed.

Environmental indicators for construction planning are identified and sorted by their environmental impacts (EI_i) in Table 3.7. The value of environmental impacts for each environmental indicator $i(EI_i)$ is calculated using Equation 3.7, which is a sum of eight generally recognized but most serious environmental hazards caused by the indicator. These eight hazards include soil and ground

Table 3.6 A statistical classification of referred articles on environmental issues

Research highlight	*Reference and starting point*	*Reference amount (as of 31/12/2002)*	
		ASCE's CEDB (since 1972)	*EI's Compendex® (since 1970)*
Technology		94	358
Environment-friendly innovative technology	Taylor *et al.* 1976	36	65
Pollution prevention and minimization		58	293
Air pollution	Henderson 1970	–	–
Noise pollution	U.S.EPA 1971	–	–
Water pollution	McCullough and Nicklen 1971	–	–
Waste pollution	Spivey 1974a,b	–	–
Management		213	367
Environmental survey	Spivey 1974a,b	12	41
Environmental/Quality management system	Dohrenwend	11	28
Environmental/Quality management approach	Dohrenwend 1973	7	18
Information technology	Kawal 1971	183	280
Material		60	183
Eco-friendly regenerated construction material	Emery 1974	35	93
Waste re-use and recycling	Spivey 1974a,b	25	90

Notes
1 ASCE's CEDB is available online via http://www.pubs.asce.org/cedbsrch.html;
2 EI's Compendex® is available online via http://www.engineeringvillage2.org/.

contamination, ground and underground water pollution, C&D waste, noise and vibration, dust, hazardous emissions and odours, impacts on wildlife and natural features, and archaeological impacts (Chen, Li and Wong 2000).

$$\mathrm{EI}_i = \sum_{j=1}^{8} \mathrm{EI}_{i,j} \quad (j = 1, 2, \ldots, 8) \tag{3.7}$$

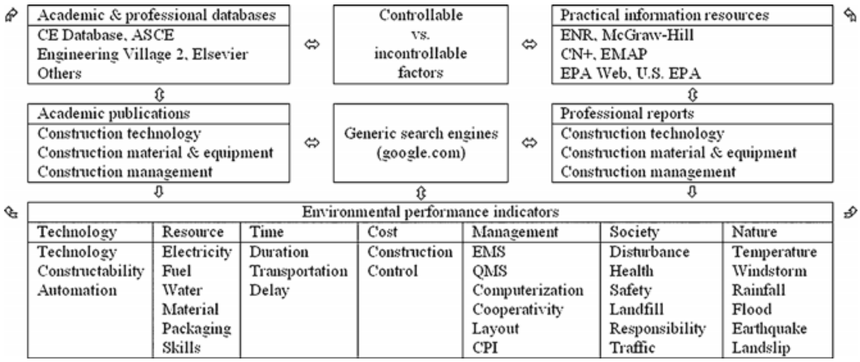


Figure 3.9 The framework for identifying environmental indicators.

where EI_i is the total environmental impact caused by environmental indicator i, and $EI_{i,j}$ is individual environmental impact caused by eight possible hazards including soil and ground contamination ($j = 1$), ground and underground water pollution ($j = 2$), C&D waste ($j = 3$), noise and vibration ($j = 4$), dust ($j = 5$), hazardous emissions and odours ($j = 6$), impacts on wildlife and natural features (j=7), and archaeological impacts ($j = 8$) caused by the environmental indicator i. Its value is defined to be one of the three choices $\{-1, 0, +1\}$; where -1 represents that the environmental indicator will intensify the level of hazards, 0 represents that the effect of the environmental indicator is uncertain, and $+1$ represents that the indicator can reduce the level of hazards.

The assumed value of environmental impact of each environmental indicator (EI_i) is then used to reclassify the environmental indicators which have been identified from the literature review so that the new classification can be more flexible to all kinds of construction projects. The environmental indicators, with their original classification, and corresponding values of $EI_{i,j}$ are listed in Table 3.7. According to the results of environmental impacts listed in Table 3.7, all environmental indicators are finally classified into EA Factors ($EI_i < 0$), EF Factors ($EI_i > 0$), and EU Factors ($EI_i = 0$) (refer to Table 3.8). These reclassified environmental indicators are to be used for constructing an ANP model for evaluating environmental impact of a construction plan.

In addition to the classification of these environmental indicators and their EI_i values, Table 3.8 also provides corresponding values of experimental plan alternatives Plan A, Plan B and Plan C, based on a construction background in Shanghai, China.

3.3.3 ANP model and approach

As defined by Saaty (1996/1999), the ANP is a general theory of relative measurement used to derive composite priority ratio scales from individual

Table 3.7 Environmental indicators and their potential environmental impacts as to a construction plan

Class	*Environmental indicators*	*Unit*	*Potential environmental impacts* (EI_i)									*Representative references*
			$EI_{i,1}$	$EI_{i,2}$	$EI_{i,3}$	$EI_{i,4}$	$EI_{i,5}$	$EI_{i,6}$	$EI_{i,7}$	$EI_{i,8}$	$\sum_{j=1}^{8} EI_{i,j}$	
Technology	Cleaner technologies and Automation ratio	%	+1	+1	+1	+1	+1	+1	+1	+1	+8	Rosenfeld and Shapira 1998; Jones and Klassen 2001; Tiwari 2001; Reddy and Jagadish 2003
	Constructability	%	0	0	0	0	0	0	0	0	0	Mifkovic and Peterson 1975; Hinckley 1986; Bonforte and Keeber 1993
Resource	Electricity consumption amount	kWh	0	0	−1	−1	−1	−1	0	0	−4	Hendrickson and Horvath 2000
	Fuel consumption amount	joule	−1	−1	−1	−1	−1	−1	−1	−1	−8	Mohr 1975; Peyton 1977; Reardon 1995; Peurifoy 2002
	Water consumption amount	ton	−1	−1	−1	0	+1	0	−1	0	−4	Gambatese and James 2001
	Wastewater treatment/re-use ratio	%	+1	+1	+1	0	0	0	0	0	+3	Leung 1999
	Material serviceability	%	0	0	+1	0	0	0	0	0	+1	Orofino 1989; Suprenant 1990; Horvath and Hendrickson 1998; Lippiatt 1999
	Material durability	%	+1	+1	+1	0	0	0	0	0	+3	Orofino 1989; Suprenant 1990; Horvath and Hendrickson 1998; Lippiatt 1999
	Cargo packaging recycling ratio	%	0	0	+1	0	+1	+1	0	0	+3	Ross and Evans 2003
	Generative material use ratio	%	0	0	0	0	0	0	0	0	0	Austin 1991; Masters 2001; Enkawa and Schvaneveldt 2001; Sawhney *et al.* 2002; Reddy and Jagadish 2003
	Waste generating rate	%	−1	−1	−1	0	−1	0	0	0	−4	Gavilan and Bernold 1994

Table 3.7 (Continued)

Class	*Environmental indicators*	*Unit*	*Potential environmental impacts* (EI_i)									*Representative references*
			$EI_{i,1}$	$EI_{i,2}$	$EI_{i,3}$	$EI_{i,4}$	$EI_{i,5}$	$EI_{i,6}$	$EI_{i,7}$	$EI_{i,8}$	$\sum_{j=1}^{8} EI_{i,j}$	
	Waste re-use and recycling ratio	%	+1	0	+1	0	0	0	0	0	+2	Walter 1976; Gidley and Sack 1984; Rhatigan and Irwin 2001
	Health and safety risk to staff	%	0	0	0	+1	+1	+1	+1	0	+4	Morris 1976; Wong *et al.* 1985; Austin 1991; Sauni *et al.* 2001; Abdelhamid and Everett 1999; Bello *et al.* 2002
	Required skills on staff	%	0	0	+1	0	+1	0	0	0	+2	Chen 2003
Time	Construction duration	day	−1	−1	−1	−1	−1	−1	−1	−1	−8	Morris and Novak 1976
	Transportation time	hour	0	0	0	−1	−1	−1	−1	11	−5	Bernstein 1983
	Construction delay risk	hour	0	0	−1	0	−1	−1	0	0	−3	Suprenant and Malisch 2000
Cost	Construction cost	$	−1	−1	−1	−1	−1	−1	−1	−1	−8	Koehn 1976
	Environmental control cost	$	+1	+1	+1	+1	+1	+1	+1	+1	+8	Parker 1998
Management	ISO 14001 EMS adoption	%	+1	+1	+1	+1	+1	+1	+1	+1	+8	Kloepfer 1997
	ISO 9001 QMS adoption	%	0	0	0	0	0	0	0	0	0	Osuagwu 2002; Escanciano *et al.* 2002

	Computerizations	%	+1	+1	+1	+1	+1	+1	+1	+1	+8	Sailor 1974; Arnfalk 1999
	Cooperativity/ Unionization risk	%	+1	+1	+1	+1	+1	+1	+1	+1	+8	Schodek 1976
	Site layout suitability	%	+1	+1	+1	+1	+1	+1	+1	+1	+8	Tatum 1978
Society	Public health and safety risk	%	−1	−1	−1	−1	−1	−1	0	0	−6	Griffith 1994; U.S.EPA 2002a,b,c
	Waste disposal price	$	+1	+1	+1	+1	+1	+1	+1	+1	+8	Austin 1991
	Legal involvements	%	+1	+1	+1	+1	+1	+1	+1	+1	+8	Lavers and Shiers 2000; Grigg *et al.* 2001
	Public traffic disruptions	day	0	0	0	−1	−1	−1	−1	0	−4	USEPA 2002a; USEPA 2002b; USEPA 2002c
	Cargo transportation burden	ton-mile	0	0	0	−1	−1	−1	−1	0	−4	USEPA 2002a; USEPA 2002b; USEPA 2002c
Nature	Temperature affection risk	%	0	−1	−1	0	−1	0	0	0	−3	Morris 1976; Tian 2002
	Storm affection risk	%	0	0	−1	0	−1	−1	0	0	−3	Rutherford 1981; Sparks *et al.* 1989; Carper 1990
	Earthquake affection risk	%	−1	−1	−1	0	−1	−1	0	0	−5	Islam and Hashmi 1999; Maitra 1999; Rosowsky 2002

Notes

1 Definition of $EI_{i,j}$: $EI_{i,1}$ represents environmental impact for soil and ground contamination, $EI_{i,2}$ represents environmental impact for ground and underground water, $EI_{i,3}$ represents environmental impact for C and D waste, $EI_{i,4}$ represents environmental impact for noise and vibration, $EI_{i,5}$ represents environmental impact for dust, $EI_{i,6}$ represents environmental impact for hazardous emissions and odours, $EI_{i,7}$ represents environmental impact on wildlife and natural features, and $EI_{i,8}$ represents environmental impact on archaeology.

2 Empirical value of $EI_{i,j}$: $EI_{i,j} \in = (-1, 0, +1)$ (−1 represents adverse environmental impact, 0 represents indefinite environmental impact, and 1 represents favourable environmental impact).

3 Kilowatt-hour (kWh): The kilowatt-hour (symbolized kWh) is a unit of energy equivalent to one kilowatt (1 kW) of power expended for one hour (1 h) of time. An energy expenditure of 1 kWh represents 3,600,000 joules (3.600×10^6 J).

Source: http://whatis.techtarget.com/

Table 3.8 Environmental indicators and corresponding values of plan alternatives for the ANP model

Classification	*Environmental indicators*		*Unit*	EI_i	*Plan alternatives*		
					Plan A	*Plan B*	*Plan C*
1 EA Factors	1.1	Fuel consumption amount (FCA)	Mjoule	−8	36k	45k	49k
	1.2	Construction duration (COD)	day	−8	500	560	450
	1.3	Construction cost (COC)	M$	−8	30	31	29
	1.4	Public health and safety risk (PHS)	%	−6	10	20	25
	1.5	Transportation time (TRT)	hour	−5	4.0k	4.5k	4.8k
	1.6	Earthquake affection risk (EAR)	%	−5	0.01	0.01	0.01
	1.7	Electricity consumption amount (ECA)	kWh	−4	30k	45k	50k
	1.8	Water consumption amount (WCA)	ton	−4	3.1k	3.8k	4.1k
	1.9	Waste generating rate (WGR)	%	−4	1.2	3.0	3.5
	1.10	Public traffic disruptions (PTD)	day	−4	39	60	70
	1.11	Cargo transportation burden (CTB)	ton-mile	−4	450k	500k	550k
	1.12	Construction delay risk (CDR)	hour	−3	150	200	220
	1.13	Temperature affection risk (TAR)	%	−3	10.0	8.9	8.7
	1.14	Storm affection risk (SAR)	%	−3	2.0	1.8	1.8
2 EU Factors	2.1	Constructability (COB)	%	0	100	100	100
	2.2	Generative material use ratio (GMU)	%	0	20	10	8
	2.3	ISO 9001 QMS adoption (QMS)	%	0	100	100	100
3 EF Factors	3.1	Cleaner technologies/ Automation ratio (CTA)	%	+8	80	50	40
	3.2	Computerizations (PCA)	%	+8	80	80	80
	3.3	Environmental control cost (ECC)	M$	+8	0.8	0.5	0.5
	3.4	ISO 14001 EMS adoption (EMS)	%	+8	0	0	0

3.5	Cooperativity/Unionization risk (COP)	%	+8	100	80	60
3.6	Site layout suitability (SLS)	%	+8	80	60	50
3.7	Waste disposal price (WDP)	M$	+8	0.10	0.25	0.29
3.8	Legal and responsibility risk (LRR)	%	+8	0.10	0.23	0.32
3.9	Health and safety risk to staff (HSR)	%	+4	0.10	0.21	0.28
3.10	Wastewater treatment/ re-use ratio (WTR)	%	+3	90	50	40
3.11	Material durability (MAD)	%	+3	100	80	80
3.12	Cargo packaging recycling ratio (CPR)	%	+3	100	50	0
3.13	Waste re-use and recycling ratio (WRR)	%	+2	90	30	35
3.14	Required skills on staff (RSS)	%	+2	80	60	60
3.15	Material serviceability (MAS)	%	+1	100	80	80

Notes

1 EI_i value equals to $\Sigma EI_{i,j}$ (refer to Table 3.7);

2 EA Factors means environmental-adverse factors, EF Factors means environmental-friendly factors, and EU Factors means environmental-uncertainty factors;

3 The corresponding value of plan alternatives is calculated based on relative information and data in each construction plan alternative and no formulas and details have been provided for these calculations in this chapter.

ratio scales that represent relative measurements of the influence of elements that interact with respect to control criteria. The ANP is a coupling of two parts: one is a control hierarchy or network of criteria and subcriteria that control the interactions (interdependencies and feedback), another is a network of influences among the nodes and clusters. Moreover, the control hierarchy is a hierarchy of criteria and subcriteria for which priorities are derived in the usual way with respect to the goal of the system being considered. The criteria are used to compare the components of a system, and the subcriteria are used to compare the elements of a component. Steps of the ANP analysis for the environmental-conscious construction planning are laid out from Step A to Step D:

3.3.3.1 Step A: ANP model construction

This step aims to construct an ANP model for evaluation based on determining the control hierarchies such as benefits, costs, opportunities, and risk, as well as the corresponding criterion for comparing the components (clusters) of the system and sub-criteria for comparing the elements of the system, together with a determination of the clusters with their elements for each control criterion or subcriterion.

The env.Plan model is outlined in Figure 3.10. The decision environment consists of external environment and internal environment. In the exterior env.Plan environment, the downward arrow indicates the process of transferring data required by the ANP, the upward arrow indicates the process of feedback with evaluation results from the ANP, and the feedback process (loop) between the external environment and the internal environment indicates a circulating pipe for environmental priority evaluation of alternative construction plans. In the internal env.Plan environment, connections among four clusters and 35 nodes are modelled by two-way and looped arrows to describe the existing interdependencies. The four clusters are Plan Alternatives (C_1), EA Factors (C_2), EU Factors (C_3), and EF Factors (C_4). In correspondence with the four clusters, there are 35 nodes including 3 nodes in C_1 ($N_{11\sim3}$), 14 nodes in C_2 ($N_{21\sim14}$), 3 nodes in C_3 ($N_{31\sim3}$) and 15 nodes in C_4 ($N_{41\sim15}$). Figure 3.10 illustrates the

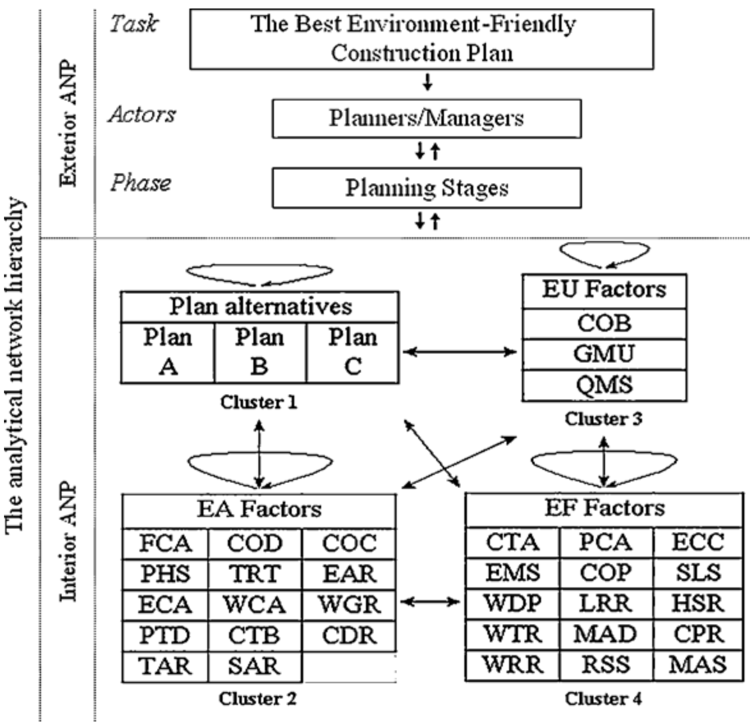


Figure 3.10 The env.Plan ANP environment.

env.Plan model implemented using an ANP with all interior clusters and nodes, and exterior related participators.

Concerning the interdependencies between any two clusters and any two nodes, the env.Plan model structured here is a simple ANP model containing feedback and self-loops among the clusters but with no control structure because there is an implicit control criterion with respect to which all judgements (paired comparisons) are made in this model: environmental impact. For example, when comparing the cluster EA Factors (C_2) to cluster EF Factors (C_4), the latter is obviously more important for reducing negative environmental impacts, and similarly when the node comparisons are made (see Step B), relative importance of the nodes can be decided in the same way. Table 3.7 provides a list of 32 environmental indicators used in constructing the ANP model and the corresponding references from which the indicator is retrieved.

3.3.3.2 Step B: Paired comparisons

This step aims to perform pairwise comparisons among the clusters, as well as pairwise comparisons between nodes, as they are interdependent. On completing the pairwise comparisons, the relative importance weight (denoted as a_{ij}) of interdependence is determined by using a scale of pairwise judgement, where the relative importance weight is valued from 1 to 9 (Saaty 1996). The fundamental scale of pairwise judgement is given in Table 3.9. The weight of interdependence is determined by a human decision-maker who is abreast with professional experience and knowledge in the application area. In this study, it is determined subjectively as the objective of this study is mainly to demonstrate the usefulness of the ANP model in evaluating the potential environmental impact due to the execution of a construction plan.

Weights for all interdependencies for a particular construction plan are then aggregated into a series of submatrices. For example, if the cluster of plan alternatives includes Plans A, B, and C, and each of the plans is connected to nodes in

Table 3.9 Pairwise judgements of indicator *i*

Pairwise judgement		1	2	3	4	5	6	7	8	9
Indicator *i*	Plan A	**x**	**x**	✓	**x**	**x**	**x**	**x**	**x**	**x**
	Plan B	**x**	**x**	**x**	**x**	✓	**x**	**x**	**x**	**x**
	Plan C	**x**	**x**	**x**	**x**	**x**	**x**	✓	**x**	**x**
Indicator I_i	Indicator I_j	**x**	**x**	**x**	**x**	✓	**x**	**x**	**x**	**x**

Notes

1 The symbol **x** denotes item under selection for pairwise judgement, and the symbol ✓ denotes selected pairwise judgement.

2 Scale of pairwise judgement: 1 equal, 2 equally to moderately dominant, 3 moderately dominant, 4 moderately to strongly dominant, 5 strongly dominant, 6 strongly to very strongly dominant, 7 very strongly dominant, 8 very strongly to extremely dominant, 9 extremely dominant.

Table 3.10 Formulation of supermatrix and its submatrix for env.Plan

Supermatrix	*Submatrix*
$W = \begin{bmatrix} W_{11} & W_{12} & W_{13} & W_{14} \\ W_{21} & W_{22} & W_{23} & W_{24} \\ W_{31} & W_{32} & W_{33} & W_{34} \\ W_{41} & W_{42} & W_{43} & W_{44} \end{bmatrix}$ $Cluster: C_1 \quad C_2 \quad C_3 \quad C_4$ $Node: N_{1_{1\sim3}} \quad N_{2_{1\sim14}} \quad N_{3_{1\sim3}} \quad N_{4_{1\sim15}}$	$W_{IJ} = \begin{bmatrix} w_1 \|_{I,J} & \cdots & w_1 \|_{I,J} \\ w_2 \|_{I,J} & \cdots & w_2 \|_{I,J} \\ \cdots & \cdots & \cdots \\ w_i \|_{I,J} & \cdots & w_i \|_{I,J} \\ \cdots & \cdots & \cdots \\ w_{N_{I_1}} \|_{I,J} & \cdots & w_{N_{I_n}} \|_{I,J} \end{bmatrix}$

Notes

I is the index number of rows; and J is the index number of columns; both I and J correspond to the number of cluster and their nodes ($I, J \in (1, 2, \ldots, 35)$), N_I is the total number of nodes in cluster I, n is the total number of columns in cluster I. Thus a 35×35 supermatrix is formed.

the cluster of EF Factors, pairwise judgements of the cluster will result in relative weights of importance between each plan alternative and each EF Factor. The aggregation of the weights thus forms a 3×14 submatrix located at "W_{21}" in Table 3.10. It is necessary to note that pairwise comparisons are necessary to all connections (clusters and nodes) in the ANP model to identify the level of interdependencies which are fundamental in the ANP procedure. The series of submatrices are then aggregated into a supermatrix which is denoted as supermatrix A in this study, and it will be used to derive the initial supermatrix in the later calculation in Step C.

Table 3.9 gives a general form for pairwise judgement among environmental indicators and construction plan alternatives, which is adopted in this study. For example, for the environmental indicator 1.1 Fuel consumption amount (FCA) (EA Factor 1), the pairwise judgements are as given in Table 3.9, as the fuel consumption in Plan A is the least among the three plan alternatives, whilst the fuel consumption in Plan C is the highest; in addition to this judgement in property, quantitative pairwise judgements are also made in order to define plan alternatives' priorities. After finishing a series of pairwise judgements, from environmental indicator i to environmental indicator n, the calculation of the ANP can thus be conducted following the Step C to the Step D. Besides the pairwise judgement between an environmental indicator and a construction plan, the developed env.Plan model contains all other pairwise judgements between each of the environmental indicators (indicator I_i and indicator I_j in Table 3.9) and this essential initialization is set up based on the quantitative attribute of each plan alternative which has been given in Table 3.8.

3.3.3.3 Step C: Supermatrix calculation

This step aims to form a synthesized supermatrix to allow for the resolution of the effects of the interdependencies that exist between the elements (nodes and clusters) of the ANP model. The supermatrix of the env.Plan model is a two-dimensional partitioned matrix consisting of 16 submatrices (refer to Table 3.10).

In order to obtain useful information for construction plan selection, the calculation of the supermatrix is to be done following three substeps which transform an initial supermatrix to a weighted supermatrix, and then to a synthesized supermatrix.

At first, an initial supermatrix of the ANP model is created. The initial supermatrix consists of local priority vectors obtained from the pairwise comparisons among clusters and nodes. A local priority vector is an array of weight priorities containing a single column (denoted as $w^{\mathrm{T}} = (w_1, w_2, \ldots, w_i, \ldots, w_n)$), whose components (denoted as w_i) are derived from a judgement comparison matrix A and deduced by Equation 3.8 (Saaty 2001).

$$w_i \Big|_{I,J} = \sum_{i=1}^{I} \frac{\left(\frac{a_{ij}}{\sum_{j=1}^{J} a_{ij}} \right)}{J} \tag{3.8}$$

where $w_i \Big|_{I,J}$ is the weighted/derived priority of node i at row I and column J; a_{ij} is a matrix value assigned to the interdependence relationship of node i to node j. The initial supermatrix is constructed by substituting the submatrices into the supermatrix as indicated in Table 3.10. A detail of the initial supermatrix is given in Table 3.11.

After the formation of the initial supermatrix, it is transformed into a weighted supermatrix. This process involves multiplying every node in a cluster of the initial supermatrix by the weight of the cluster, which has been established by pairwise comparison among the four clusters. In the weighted supermatrix, each column is stochastic, i.e. sum of the column amounts to 1 (Saaty 2001) (refer to Table 3.12).

The last substep is to compose a limiting supermatrix, which is to raise the weighted supermatrix to powers until it converges/stabilizes, i.e. when all the columns in the supermatrix have the same values. Saaty (1996) indicated that as long as the weighted supermatrix is stochastic, a meaningful limiting result can be obtained for prediction. A limiting supermatrix can be arrived at by taking repeatedly the power of the matrix, i.e. the original weighted supermatrix, its square, its cube, etc., until the limit is attained (converges), in which case all the numbers in each row will become identical. Calculus-type algorithm is employed in the software environment of Super Decisions, designed by Bill Adams and the Creative Decision Foundation, to facilitate the formation of the limiting supermatrix, and the calculation result is listed in Table 3.12.

The formulations of supermatrices and submatrices used in the env.Plan model are illustrated in Table 3.11, and calculation results of the initial supermatrix, the weighted supermatrix, and the limiting supermatrix are given in Tables 3.11 and 3.12. As the limiting supermatrix is set up, the next step is to select a proper plan alternative using results from the limiting supermatrix.

Table 3.11 The supermatrix for the complicated env.Plan model: initial supermatrix

Super matrix	Cluster		Plan alternatives			EA factors													EU factors			EF factors																		
		Node	Plan A	Plan B	Plan C	FCA	COD	COC	PHS	TRT	EAR	ECA	WCA	WGR	PTD	CTB	CDR	TAR	SAR	COB	GMU	QMS	CTA	PCA	ECC	EMS	COP	SLS	WDP	LRR	HSR	WTR	MAD	CPR	WRR	RSS	MAS
Initial supermatrix	Plans	PlanA	0.59173	0.67381	0.66942	0.58155	0.76116	0.71738	0.61185	0.57143	0.70097	0.70735	0.65865	0.66120	0.65707	0.69096	0.74291	0.77202	0.73338	0.24883	0.40648	0.59891	0.65308	0.41261	0.33194	0.72574	0.25000	0.49339	0.65003	0.67491	0.71881	0.70905	0.75825	0.74074	0.74446	0.77858	0.70735
		PlanB	0.33322	0.22554	0.24264	0.30900	0.16623	0.19420	0.17890	0.28571	0.19288	0.17003	0.15618	0.27178	0.19631	0.21764	0.18671	0.17344	0.19907	0.15606	0.26024	0.12619	0.25069	0.32749	0.13879	0.21221	0.25000	0.19580	0.17443	0.22385	0.22335	0.21184	0.09051	0.18518	0.14990	0.14282	0.17003
		PlanC	0.07506	0.10065	0.08795	0.10945	0.07261	0.08842	0.20925	0.14286	0.10615	0.12262	0.18517	0.06703	0.14663	0.09140	0.07038	0.05455	0.06754	0.59511	0.33328	0.27491	0.09623	0.25990	0.52926	0.06205	0.50000	0.31081	0.17553	0.10124	0.05783	0.07911	0.15125	0.07407	0.10564	0.07860	0.12262
	EA factors	FCA	0.10534	0.11897	0.08027	0.00000	0.10956	0.06693	0.05852	0.08534	0.08051	0.12142	0.04187	0.10848	0.16334	0.06290	0.08018	0.08553	0.12853	0.10717	0.06976	0.09477	0.09090	0.09182	0.12693	0.11094	0.10905	0.07435	0.09544	0.08839	0.07943	0.10799	0.09429	0.08013	0.08565	0.11627	0.12823
		COD	0.08575	0.09606	0.06923	0.06614	0.00000	0.07155	0.06768	0.07937	0.09047	0.09891	0.08121	0.13433	0.11498	0.11408	0.07879	0.06744	0.10216	0.12303	0.07093	0.06816	0.10367	0.08708	0.08669	0.05887	0.10506	0.07630	0.10706	0.10523	0.08640	0.05556	0.07038	0.10552	0.08386	0.07824	0.09811
		COC	0.10967	0.06625	0.08715	0.09591	0.10821	0.00000	0.05006	0.05355	0.07583	0.12965	0.06155	0.07063	0.11884	0.06309	0.07953	0.06175	0.09594	0.11593	0.07627	0.06524	0.07906	0.11574	0.06963	0.08676	0.07471	0.12042	0.08510	0.09669	0.06815	0.11560	0.08776	0.06663	0.06872	0.17051	0.07477
		PHS	0.05896	0.08657	0.07203	0.27822	0.09669	0.08462	0.00000	0.11144	0.08037	0.14763	0.06968	0.03993	0.11363	0.03904	0.07055	0.04312	0.05655	0.07327	0.08398	0.08717	0.08476	0.06818	0.08647	0.10097	0.07580	0.07833	0.06913	0.09519	0.09487	0.06883	0.07414	0.08194	0.09510	0.15673	0.09756
		TRT	0.07590	0.08339	0.06735	0.06214	0.07140	0.07135	0.07358	0.00000	0.13044	0.08627	0.10738	0.06886	0.09180	0.09052	0.07067	0.08738	0.07708	0.07582	0.08128	0.05877	0.06138	0.08113	0.08310	0.07317	0.10513	0.06010	0.09430	0.09627	0.07280	0.09479	0.10098	0.08221	0.10656	0.09161	0.07868
		EAR	0.06053	0.08280	0.05976	0.00003	0.05976	0.07150	0.05791	0.08777	0.00000	0.05205	0.13726	0.05821	0.05674	0.07260	0.05418	0.06642	0.05731	0.05076	0.07447	0.07723	0.07211	0.06421	0.05552	0.05638	0.07040	0.08161	0.04763	0.07413	0.08221	0.06940	0.08915	0.07734	0.04626	0.07756	0.05108
		ECA	0.05575	0.05925	0.07108	0.04919	0.07821	0.07640	0.07685	0.08411	0.07698	0.00000	0.03969	0.05573	0.05169	0.07886	0.14818	0.09097	0.06826	0.04905	0.08010	0.06232	0.08928	0.05490	0.05464	0.04990	0.04380	0.08970	0.07423	0.05697	0.04882	0.07608	0.07864	0.08077	0.06474	0.07102	0.05837
		WCA	0.09342	0.05505	0.06545	0.09751	0.08669	0.06784	0.09035	0.09319	0.07881	0.07212	0.00000	0.11684	0.05195	0.07231	0.06587	0.07832	0.10490	0.06009	0.07301	0.07579	0.06351	0.09442	0.05482	0.07291	0.06960	0.06287	0.07295	0.05726	0.07828	0.07011	0.08152	0.08179	0.05727	0.06105	0.06977
		WGR	0.03059	0.04846	0.06521	0.12876	0.06777	0.10128	0.07991	0.05533	0.07414	0.04960	0.05087	0.00000	0.05465	0.09608	0.07497	0.09068	0.04307	0.07087	0.05652	0.06354	0.05516	0.08894	0.06262	0.07361	0.08156	0.08571	0.09631	0.06634	0.05054	0.05436	0.05144	0.03810	0.05216	0.05365	0.05570
		PTD	0.06184	0.06204	0.07164	0.11627	0.06849	0.06940	0.05780	0.04722	0.09445	0.05766	0.04220	0.06152	0.00000	0.05354	0.07184	0.13666	0.09464	0.06493	0.07041	0.07286	0.04193	0.05352	0.09505	0.05713	0.05422	0.06941	0.04372	0.06928	0.09103	0.07118	0.05815	0.05364	0.05767	0.04401	0.06551
		CTB	0.06683	0.06364	0.09214	0.00003	0.06091	0.07960	0.10298	0.08735	0.06928	0.06846	0.07381	0.05853	0.03781	0.00000	0.07495	0.07988	0.07465	0.07285	0.08415	0.08009	0.08492	0.05577	0.05653	0.04703	0.03780	0.04502	0.07692	0.05753	0.07724	0.05953	0.06575	0.07065	0.09614	0.02502	0.05047
		CDR	0.06287	0.04898	0.06476	0.10576	0.08005	0.08740	0.10315	0.04911	0.07998	0.05219	0.08987	0.06021	0.04510	0.06485	0.00000	0.06476	0.05492	0.04346	0.06590	0.06627	0.05238	0.03381	0.06026	0.09537	0.06865	0.04420	0.03896	0.05117	0.07766	0.06578	0.04369	0.06112	0.07515	0.00775	0.04076
		TAR	0.07424	0.07131	0.07187	0.00003	0.06490	0.08447	0.07536	0.09023	0.03723	0.03565	0.09898	0.11297	0.05414	0.07815	0.06487	0.00000	0.04198	0.04644	0.06052	0.06369	0.05317	0.09109	0.04790	0.06707	0.05448	0.04909	0.03941	0.04393	0.03756	0.03835	0.05424	0.08642	0.05712	0.03526	0.04732
		SAR	0.05830	0.05724	0.06205	0.00003	0.04736	0.06765	0.10587	0.07599	0.03151	0.02838	0.10564	0.05377	0.04533	0.11399	0.06542	0.04709	0.00000	0.04633	0.05271	0.06409	0.06778	0.01940	0.05984	0.04989	0.04974	0.06290	0.05883	0.04163	0.05501	0.05243	0.04987	0.03374	0.05361	0.01133	0.08368
	EU factors	COB	0.14663	0.65481	0.32749	0.33333	0.25992	0.28488	0.57691	0.59567	0.64422	0.63484	0.51020	0.30769	0.21038	0.63699	0.23771	0.45995	0.54981	0.00000	0.66667	0.83333	0.21184	0.67816	0.42857	0.69096	0.43306	0.07558	0.35843	0.09362	0.28150	0.26837	0.54981	0.21764	0.39146	0.65065	0.27056
		GMU	0.19631	0.09534	0.25990	0.33333	0.41260	0.21739	0.08110	0.30848	0.08522	0.07796	0.33381	0.07692	0.42385	0.10473	0.60719	0.22113	0.36806	0.33333	0.00000	0.16667	0.07911	0.14242	0.14286	0.09140	0.10050	0.69521	0.30885	0.62411	0.17494	0.11722	0.08213	0.69096	0.27841	0.12683	0.64422
		QMS	0.65707	0.24986	0.41261	0.33333	0.32748	0.49773	0.34200	0.09585	0.27056	0.28720	0.15600	0.61539	0.36577	0.25828	0.15510	0.31892	0.08213	0.66667	0.33333	0.00000	0.70905	0.17942	0.42857	0.21764	0.46644	0.22922	0.33272	0.28227	0.54355	0.61441	0.36806	0.09140	0.33013	0.22252	0.08522
	EF factors	CTA	0.06978	0.13581	0.09747	0.08541	0.12058	0.07396	0.07200	0.05038	0.06935	0.09011	0.08748	0.07074	0.05165	0.08325	0.17483	0.07979	0.05076	0.08972	0.09466	0.08421	0.00000	0.06791	0.09726	0.07905	0.07995	0.08398	0.09585	0.07552	0.11789	0.08479	0.11562	0.07246	0.07493	0.08947	0.05433
		PCA	0.06765	0.10166	0.06898	0.07213	0.10517	0.07433	0.06863	0.07873	0.11342	0.05564	0.08112	0.06453	0.06474	0.06052	0.07122	0.06746	0.06890	0.09150	0.08175	0.04338	0.08162	0.00000	0.07706	0.05764	0.10059	0.08513	0.13292	0.08269	0.08543	0.10780	0.09512	0.07526	0.10719	0.10402	0.07714
		ECC	0.04528	0.07058	0.07280	0.06653	0.08054	0.06898	0.06085	0.05897	0.11526	0.06928	0.08142	0.06853	0.07147	0.07039	0.13798	0.05209	0.06317	0.09652	0.07732	0.08372	0.08985	0.12482	0.00000	0.10093	0.09452	0.06109	0.07433	0.06940	0.06606	0.08457	0.10003	0.07261	0.10268	0.10218	0.08153
		EMS	0.07303	0.09716	0.04755	0.07644	0.07295	0.06155	0.07930	0.06325	0.06595	0.07934	0.06952	0.05622	0.06539	0.06242	0.11292	0.05924	0.09940	0.08495	0.07807	0.05746	0.06197	0.05388	0.08136	0.00000	0.06772	0.07217	0.05960	0.03993	0.07416	0.11041	0.08678	0.07107	0.06924	0.07954	0.07248
		COP	0.07325	0.05540	0.08961	0.07072	0.07120	0.08342	0.05428	0.07395	0.05102	0.07549	0.09550	0.09723	0.05547	0.06535	0.09721	0.08351	0.05295	0.06380	0.07241	0.10434	0.05613	0.07541	0.06079	0.07437	0.00000	0.09136	0.11458	0.07763	0.08908	0.10088	0.06598	0.06965	0.09144	0.07724	0.04398
		SLS	0.07273	0.09930	0.07944	0.05045	0.04997	0.04530	0.09840	0.05725	0.05402	0.07848	0.06171	0.07328	0.09160	0.07219	0.08442	0.09874	0.08300	0.06477	0.05290	0.08149	0.06885	0.09060	0.07502	0.08543	0.05501	0.00000	0.08388	0.10075	0.09265	0.07554	0.09617	0.08762	0.05689	0.07970	0.06888
		WDP	0.06701	0.04032	0.03982	0.08386	0.05507	0.02491	0.06818	0.07712	0.08193	0.04684	0.10862	0.07793	0.07888	0.08796	0.06049	0.08256	0.06858	0.06005	0.03884	0.07142	0.07238	0.05282	0.05302	0.04019	0.07674	0.06576	0.00000	0.04635	0.05999	0.08680	0.05677	0.09358	0.06093	0.08033	0.08480
		LRR	0.05020	0.04022	0.07242	0.03047	0.06676	0.07938	0.04408	0.05815	0.06766	0.03772	0.02836	0.06558	0.05455	0.08147	0.03434	0.05674	0.06652	0.06669	0.06538	0.06280	0.05217	0.07690	0.04572	0.08360	0.08920	0.08440	0.05026	0.00000	0.10495	0.06605	0.06553	0.05851	0.05535	0.08228	0.07084
		HSR	0.09017	0.07464	0.08631	0.04293	0.05494	0.07725	0.07469	0.05417	0.06595	0.06957	0.06516	0.04750	0.05151	0.08844	0.02392	0.07661	0.06037	0.04745	0.06102	0.05742	0.07679	0.09456	0.07196	0.05625	0.06553	0.06844	0.05254	0.12612	0.00000	0.07628	0.07745	0.04634	0.05996	0.04719	0.06779
		WTR	0.04907	0.03931	0.05085	0.05552	0.06893	0.04367	0.05882	0.08600	0.04791	0.05678	0.02535	0.04918	0.08239	0.05309	0.02290	0.06716	0.09108	0.05567	0.04848	0.04056	0.08948	0.07601	0.08436	0.06750	0.08223	0.05880	0.05484	0.09333	0.03897	0.00000	0.06445	0.10172	0.07737	0.06165	0.08999
		MAD	0.08851	0.03819	0.07871	0.06837	0.06154	0.07590	0.06150	0.08811	0.06500	0.06816	0.08073	0.06791	0.07243	0.03851	0.03429	0.05593	0.07447	0.05849	0.06484	0.07627	0.06475	0.03850	0.09050	0.05727	0.05464	0.06395	0.04192	0.07855	0.07380	0.07604	0.00000	0.08634	0.10036	0.05105	0.05797
		CPR	0.07507	0.03948	0.02564	0.07972	0.05084	0.05727	0.03913	0.05334	0.05722	0.05940	0.02041	0.05137	0.08164	0.06558	0.02648	0.06248	0.04896	0.06564	0.05972	0.06524	0.08317	0.07762	0.07752	0.10130	0.05818	0.07710	0.08736	0.05861	0.04136	0.02714	0.05039	0.00000	0.05395	0.04600	0.05540
		WRR	0.06955	0.06796	0.07446	0.08191	0.04750	0.07615	0.07372	0.07670	0.05971	0.10870	0.08119	0.06394	0.07829	0.04381	0.05278	0.04768	0.06532	0.07241	0.06496	0.06964	0.07278	0.05289	0.09420	0.05269	0.05467	0.07967	0.03596	0.05047	0.07056	0.03930	0.04360	0.06986	0.00000	0.04699	0.06954
		RSS	0.05114	0.03281	0.04609	0.07877	0.04541	0.09009	0.04965	0.05091	0.05022	0.03130	0.09731	0.09745	0.05323	0.05240	0.03455	0.06509	0.06175	0.04363	0.06013	0.05468	0.06523	0.06127	0.03005	0.06801	0.05792	0.06225	0.07039	0.03455	0.04372	0.06441	0.04255	0.03405	0.05294	0.00000	0.07032
		MAS	0.05756	0.06716	0.06984	0.05677	0.04858	0.06782	0.09677	0.07297	0.03539	0.07320	0.01613	0.04860	0.04675	0.07463	0.03166	0.04493	0.04477	0.03871	0.07954	0.04738	0.06482	0.05682	0.06118	0.07577	0.06311	0.04589	0.04560	0.06611	0.04140	0.00000	0.03956	0.06092	0.03678	0.05235	0.03500

Table 3.12 The supermatrix for the complicated env.Plan model: weighted and limiting supermatrices

Super matrix	Cluster	Node	Plan A	Plan B	Plan C	FCA	COD	COC	PHS	TRT	EAR	ECA	WCA	WGR	PTD	CTB	CDR	TAR	SAR
			Plan alternatives			*EA factors*													
Weighted supermatrix	Plans	Plan A	0.14793	0.16845	0.16735	0.14539	0.19029	0.17934	0.15296	0.14286	0.17524	0.17684	0.16466	0.16530	0.16427	0.17274	0.18573	0.19300	0.18335
		Plan B	0.08330	0.05638	0.06066	0.07725	0.04156	0.04855	0.04473	0.07143	0.04822	0.04251	0.03905	0.06794	0.04908	0.05441	0.04668	0.04336	0.04977
		Plan C	0.01876	0.02516	0.02199	0.02736	0.01815	0.02211	0.05231	0.03571	0.02654	0.03065	0.04629	0.01676	0.03666	0.02285	0.01760	0.01364	0.01689
	EA factors	FCA	0.02634	0.02974	0.02007	0.00000	0.02739	0.01673	0.01463	0.02134	0.02013	0.03035	0.01047	0.02712	0.04084	0.01572	0.02005	0.02138	0.03213
		COD	0.02144	0.02401	0.01731	0.01653	0.00000	0.01789	0.01692	0.01984	0.02262	0.02473	0.02030	0.03358	0.02875	0.02852	0.01970	0.01686	0.02554
		COC	0.02742	0.01656	0.02179	0.02398	0.02705	0.00000	0.01251	0.01339	0.01896	0.03241	0.01539	0.01766	0.02971	0.01577	0.01988	0.01544	0.02398
		PHS	0.01474	0.02164	0.01801	0.06956	0.02417	0.02116	0.00000	0.02786	0.02009	0.03691	0.01742	0.00998	0.02841	0.00976	0.01764	0.01078	0.01414
		TRT	0.01897	0.02085	0.01684	0.01554	0.01785	0.01784	0.01840	0.00000	0.03261	0.02157	0.02685	0.01722	0.02295	0.02263	0.01767	0.02185	0.01927
		EAR	0.01513	0.02070	0.01494	0.00001	0.01494	0.01788	0.01448	0.02194	0.00000	0.01301	0.03431	0.01455	0.01418	0.01815	0.01355	0.01661	0.01433
		ECA	0.01394	0.01481	0.01777	0.01230	0.01955	0.01910	0.01921	0.02103	0.01925	0.00000	0.00992	0.01393	0.01292	0.01972	0.03705	0.02274	0.01707
		WCA	0.02335	0.01376	0.01636	0.02438	0.02167	0.01696	0.02259	0.02330	0.01970	0.01803	0.00000	0.02921	0.01299	0.01808	0.01647	0.01958	0.02622
		WGR	0.00765	0.01212	0.01630	0.03219	0.01694	0.02532	0.01998	0.01383	0.01853	0.01240	0.01272	0.00000	0.01366	0.02402	0.01874	0.02267	0.01077
		PTD	0.01546	0.01551	0.01791	0.02907	0.01712	0.01735	0.01445	0.01181	0.02361	0.01442	0.01055	0.01538	0.00000	0.01339	0.01796	0.03417	0.02366
		CTB	0.01671	0.01591	0.02304	0.00001	0.01523	0.01990	0.02575	0.02184	0.01732	0.01711	0.01845	0.01463	0.00945	0.00000	0.01874	0.01997	0.01866
		CDR	0.01572	0.01224	0.01619	0.02644	0.02001	0.02185	0.02579	0.01228	0.02000	0.01305	0.02247	0.01505	0.01128	0.01621	0.00000	0.01619	0.01373
		TAR	0.01856	0.01783	0.01797	0.00001	0.01622	0.02112	0.01884	0.02256	0.00931	0.00891	0.02475	0.02824	0.01353	0.01954	0.01622	0.00000	0.01050
		SAR	0.01458	0.01431	0.01551	0.00001	0.01184	0.01691	0.02647	0.01900	0.00788	0.00710	0.02641	0.01344	0.01133	0.02850	0.01635	0.01177	0.00000
	EU factors	COB	0.03666	0.16370	0.08187	0.08333	0.06498	0.07122	0.14423	0.14892	0.16106	0.15871	0.12755	0.07692	0.05260	0.15925	0.05943	0.11499	0.13745
		GMU	0.04908	0.02383	0.06498	0.08333	0.10315	0.05435	0.02027	0.07712	0.02131	0.01949	0.08345	0.01923	0.10596	0.02618	0.15180	0.05528	0.09202
		QMS	0.16427	0.06246	0.10315	0.08333	0.08187	0.12443	0.08550	0.02396	0.06764	0.07180	0.03900	0.15385	0.09144	0.06457	0.03877	0.07973	0.02053
	EF factors	CTA	0.01744	0.03395	0.02437	0.02135	0.03015	0.01849	0.01800	0.01259	0.01734	0.02253	0.02187	0.01769	0.01291	0.02081	0.04371	0.01995	0.01269
		PCA	0.01691	0.02542	0.01724	0.01803	0.02629	0.01858	0.01716	0.01968	0.02836	0.01391	0.02028	0.01613	0.01619	0.01513	0.01781	0.01686	0.01722
		ECC	0.01132	0.01764	0.01820	0.01663	0.02013	0.01724	0.01521	0.01474	0.02881	0.01732	0.02035	0.01713	0.01787	0.01760	0.03450	0.01302	0.01579
		EMS	0.01826	0.02429	0.01189	0.01911	0.01824	0.01539	0.01982	0.01581	0.01649	0.01984	0.01738	0.01406	0.01635	0.01560	0.02823	0.01481	0.02485
		COP	0.01831	0.01385	0.02240	0.01768	0.01780	0.02085	0.01357	0.01849	0.01276	0.01887	0.02388	0.02431	0.01387	0.01634	0.02430	0.02088	0.01324
		SLS	0.01818	0.02482	0.01986	0.01261	0.01249	0.01133	0.02460	0.01431	0.01351	0.01962	0.01543	0.01832	0.02290	0.01805	0.02110	0.02469	0.02075
		WDP	0.01675	0.01008	0.00995	0.02097	0.01377	0.00623	0.01705	0.01928	0.02048	0.01171	0.02715	0.01948	0.01972	0.02199	0.01512	0.02064	0.01714
		LRR	0.01255	0.01006	0.01811	0.00762	0.01669	0.01985	0.01102	0.01454	0.01691	0.00943	0.00709	0.01640	0.01364	0.02037	0.00859	0.01419	0.01663
		HSR	0.02254	0.01866	0.02158	0.01073	0.01373	0.01931	0.01867	0.01354	0.01649	0.01739	0.01629	0.01188	0.01288	0.02211	0.00598	0.01915	0.01509
		WTR	0.01227	0.00983	0.01271	0.01388	0.01723	0.01092	0.01471	0.02150	0.01198	0.01419	0.00634	0.01230	0.02060	0.01327	0.00572	0.01679	0.02277
		MAD	0.02213	0.00955	0.01968	0.01709	0.01538	0.01898	0.01538	0.02203	0.01625	0.01704	0.02018	0.01698	0.01811	0.00963	0.00857	0.01398	0.01862
		CPR	0.01877	0.00987	0.00641	0.01993	0.01271	0.01432	0.00978	0.01334	0.01430	0.01485	0.00510	0.01284	0.02041	0.01640	0.00662	0.01562	0.01224
		WRR	0.01739	0.01699	0.01862	0.02048	0.01188	0.01904	0.01843	0.01917	0.01493	0.02717	0.02030	0.01598	0.01957	0.01095	0.01320	0.01192	0.01633
		RSS	0.01278	0.00820	0.01152	0.01969	0.01135	0.02252	0.01241	0.01273	0.01255	0.00782	0.02433	0.02436	0.01331	0.01310	0.00864	0.01627	0.01544
		MAS	0.01439	0.01679	0.01746	0.01419	0.01215	0.01696	0.02419	0.01824	0.00885	0.01830	0.00403	0.01215	0.01169	0.01866	0.00792	0.01123	0.01119
Limiting supermatrix		N_i^T	0.11231	0.04149	0.03543	0.03296	0.03001	0.03051	0.02979	0.02779	0.02271	0.02280	0.02551	0.02222	0.02271	0.02268	0.02091	0.02048	0.01879

Super matrix	Cluster	Node	COB	GMU	QMS	CTA	PCA	ECC	EMS	COP	SLS	WDP	LRR	HSR	WTR	MAD	CPR	WRR	RSS	MAS
			EU factors			*EF factors*														
Weighted supermatrix	Plans	Plan A	0.06221	0.10162	0.14973	0.01196	0.00755	0.00608	0.01329	0.00458	0.00903	0.01190	0.01236	0.01316	0.01298	0.01388	0.01356	0.01363	0.01425	0.01295
		Plan B	0.03902	0.06506	0.03155	0.00459	0.00600	0.00254	0.00389	0.00458	0.00358	0.00319	0.00410	0.00409	0.00388	0.00166	0.00339	0.00274	0.00261	0.00311
		Plan C	0.14878	0.08332	0.06873	0.00176	0.00476	0.00969	0.00114	0.00915	0.00569	0.00321	0.00185	0.00106	0.00145	0.00277	0.00136	0.00193	0.00144	0.00225
	EA factors	FCA	0.02679	0.01744	0.02369	0.05735	0.05793	0.08008	0.06999	0.06880	0.04691	0.06021	0.05576	0.05011	0.06813	0.05949	0.05055	0.05404	0.07335	0.08090
		COD	0.03076	0.01773	0.01704	0.06540	0.05494	0.05469	0.03714	0.06628	0.04813	0.06754	0.06639	0.05450	0.03505	0.04440	0.06657	0.05291	0.04936	0.06190
		COC	0.02898	0.01907	0.01631	0.04988	0.07301	0.04393	0.05473	0.04713	0.07597	0.05369	0.06100	0.04300	0.07293	0.05537	0.04204	0.04335	0.10757	0.04717
		PHS	0.01832	0.02099	0.02179	0.05347	0.04301	0.05455	0.06370	0.04782	0.04942	0.04361	0.06005	0.05985	0.04342	0.04678	0.05170	0.06000	0.09888	0.06155
		TRT	0.01895	0.02032	0.01469	0.03873	0.05119	0.05243	0.04616	0.06633	0.03791	0.05949	0.06073	0.04593	0.05980	0.06370	0.05186	0.06722	0.05779	0.04963
		EAR	0.01269	0.01862	0.01931	0.04549	0.04051	0.03503	0.03557	0.04442	0.05148	0.03005	0.04677	0.05186	0.04378	0.05624	0.04879	0.02919	0.04893	0.03222
		ECA	0.01226	0.02003	0.01558	0.05633	0.03463	0.03447	0.03148	0.02763	0.05659	0.04683	0.03594	0.03080	0.04800	0.04961	0.05095	0.04084	0.04480	0.03682
		WCA	0.01502	0.01825	0.01895	0.04007	0.05957	0.03458	0.04600	0.04391	0.03966	0.04602	0.03612	0.04939	0.04423	0.05143	0.05160	0.03613	0.03852	0.04401
		WGR	0.01772	0.01413	0.01589	0.03480	0.05611	0.03950	0.04644	0.05145	0.05407	0.06076	0.04185	0.03188	0.03430	0.03245	0.02404	0.03290	0.03385	0.03514
		PTD	0.01623	0.01760	0.01822	0.02645	0.03377	0.05996	0.03604	0.03421	0.04379	0.02758	0.04370	0.05743	0.04491	0.03668	0.03384	0.03638	0.02777	0.04133
		CTB	0.01821	0.02104	0.02002	0.05357	0.03518	0.03566	0.02967	0.02385	0.02841	0.04853	0.03629	0.04873	0.03756	0.04148	0.04457	0.06065	0.01578	0.03184
		CDR	0.01087	0.01647	0.01657	0.03304	0.02133	0.03802	0.06017	0.04331	0.02789	0.02458	0.03228	0.04899	0.04150	0.02757	0.03856	0.04741	0.00489	0.02571
		TAR	0.01161	0.01513	0.01592	0.03354	0.05746	0.03022	0.04231	0.03437	0.03097	0.02486	0.02771	0.02369	0.02420	0.03422	0.05452	0.03603	0.02224	0.02986
		SAR	0.01158	0.01318	0.01602	0.04276	0.01224	0.03775	0.03147	0.03138	0.03968	0.03711	0.02626	0.03471	0.03308	0.03146	0.02129	0.03382	0.00715	0.05279
	EU factors	COB	0.00000	0.16667	0.20833	0.01146	0.03668	0.02318	0.03737	0.02342	0.00409	0.01938	0.00506	0.01523	0.01451	0.02974	0.01177	0.02117	0.03519	0.01463
		GMU	0.08333	0.00000	0.04167	0.00428	0.00770	0.00773	0.00494	0.00543	0.03760	0.01670	0.03375	0.00946	0.00634	0.00444	0.03737	0.01506	0.00686	0.03484
		QMS	0.16667	0.08333	0.00000	0.03835	0.00970	0.02318	0.01177	0.02523	0.01240	0.01800	0.01527	0.02940	0.03323	0.01991	0.00494	0.01785	0.01204	0.00461
	EF factors	CTA	0.02243	0.02366	0.02105	0.00000	0.02015	0.02886	0.02346	0.02372	0.02492	0.02844	0.02241	0.03498	0.02516	0.03431	0.02150	0.02223	0.02655	0.01612
		PCA	0.02288	0.02044	0.01084	0.02422	0.00000	0.02287	0.01710	0.02985	0.02526	0.03944	0.02454	0.02535	0.03199	0.02823	0.02233	0.03181	0.03087	0.02289
		ECC	0.02413	0.01933	0.02093	0.02666	0.03704	0.00000	0.02995	0.02805	0.01813	0.02206	0.02059	0.01960	0.02509	0.02968	0.02155	0.03047	0.03032	0.02419
		EMS	0.02124	0.01952	0.01436	0.01839	0.01599	0.02414	0.00000	0.02010	0.02142	0.01768	0.01185	0.02201	0.03276	0.02575	0.02109	0.02055	0.02360	0.02151
		COP	0.01595	0.01810	0.02609	0.01666	0.02238	0.01804	0.02207	0.00000	0.02711	0.03400	0.02303	0.02643	0.02993	0.01958	0.02067	0.02713	0.02292	0.01305
		SLS	0.01619	0.01322	0.02037	0.02043	0.02688	0.02226	0.02535	0.01632	0.00000	0.02489	0.02990	0.02749	0.02242	0.02854	0.02600	0.01688	0.02365	0.02044
		WDP	0.01501	0.00971	0.01786	0.02148	0.01567	0.01573	0.01193	0.02277	0.01951	0.00000	0.01375	0.01780	0.02576	0.01685	0.02777	0.01808	0.02384	0.02516
		LRR	0.01667	0.01634	0.01570	0.01548	0.02282	0.01357	0.02481	0.02647	0.02505	0.01491	0.00000	0.03114	0.01960	0.01945	0.01736	0.01642	0.02441	0.02102
		HSR	0.01186	0.01525	0.01436	0.02279	0.02806	0.02135	0.01669	0.01945	0.02031	0.01559	0.03743	0.00000	0.02263	0.02298	0.01375	0.01779	0.01400	0.02012
		WTR	0.01392	0.01212	0.01014	0.02655	0.02255	0.02503	0.02003	0.02440	0.01745	0.01627	0.02769	0.01156	0.00000	0.01913	0.03019	0.02296	0.01829	0.02670
		MAD	0.01462	0.01621	0.01907	0.01921	0.01142	0.02685	0.01699	0.01621	0.01898	0.01244	0.02331	0.02190	0.02256	0.00000	0.02562	0.02978	0.01515	0.01720
		CPR	0.01641	0.01493	0.01631	0.02468	0.02303	0.02300	0.03006	0.01726	0.02288	0.02592	0.01739	0.01227	0.00805	0.01495	0.00000	0.01601	0.01365	0.01644
		WRR	0.01810	0.01624	0.01741	0.02160	0.01570	0.02795	0.01564	0.01622	0.02364	0.01067	0.01498	0.02094	0.01166	0.01294	0.02073	0.00000	0.01395	0.02064
		RSS	0.01091	0.01503	0.01367	0.01936	0.01818	0.00892	0.02018	0.01719	0.01847	0.02089	0.01025	0.01297	0.01911	0.01263	0.01010	0.01571	0.00000	0.02087
		MAS	0.00968	0.01989	0.01184	0.01923	0.01686	0.01816	0.02248	0.01873	0.01362	0.01353	0.01962	0.01229	0.00000	0.01174	0.01808	0.01091	0.01554	0.01039
Limiting supermatrix		N_i^T	0.08042	0.04520	0.07300	0.02196	0.02019	0.01991	0.01859	0.01942	0.01899	0.01658	0.01562	0.01725	0.01513	0.01749	0.01546	0.01721	0.01416	0.01428

Note

N_i stands for any of the 35 nodes involved in the four clusters including Plan alternatives, EA factors, EU factors, and EF factors.

3.3.3.4 Step D: Selection

This step aims to select the best construction plan based on the computation results of the limiting supermatrix of the ANP model. Main results of the ANP model computations are the overall priorities of construction plans obtained by synthesizing the priorities of individual construction plans against different environmental indicators. The selection of the best construction plan, which has the highest environmental priority, can be done using a limiting priority weight, which is defined in Equation 3.9.

$$W_i = w_{C_{\text{Plan}},i} / w_{C_{\text{Plan}}} = w_{C_{\text{Plan}},i} / (w_{C_{\text{Plan}},1} + \cdots + w_{C_{\text{Plan}},n}) \tag{3.9}$$

where W_i is the synthesized priority weight of plan alternative $i (i = 1, \ldots, n)$ (n is the total number of plan alternatives, $n = 3$ in this study), and $w_{C_{Plan},i}$ is the limited weight of plan alternative i in the limiting supermatrix. Because the $w_{C_{\text{Plan}},i}$ is transformed from pairwise judgements conducted in Step B, it is reasonable to regard it as the priority of the plan alternative i and thus to be used in Equation 3.9. According to the computation results in the limiting supermatrix in Table 3.12, $w_{C_{\text{Plan}},i} = (0.11231, 0.04149, 0.03543)$, so $W_i = (0.59351, 0.21926, 0.18723)$; as a result, the best environmental-conscious construction plan is Plan A.

In addition to the complicated env.Plan model developed in Figure 3.10, another ANP model, called simplified env.Plan model for alternative construction plan selection, was developed with 15 nodes selected from the total 35 nodes of the complicated env.Plan model in Figure 3.10. In order to decrease the number of elements in a supermatrix of the simplified env.Plan model, similar subcomponents of EF Factors are combined, including a combination of subcomponents 3.1 and 3.2 for environment-friendly construction and management technology (Technology) and a combination of subcomponents 3.3 and 3.4 for environmental control cost (ECC). Finally, the nodes for the simplified env.Plan model include FCA, COD, and COC in EA Factors cluster; COB, GMU, and QMS in the EU Factors cluster; CTA + PCA, ECC + EMS, COP, SLS, WDP, and LRR in the EF Factors cluster; and Plan A, Plan B, and Plan C in the Plan Alternatives cluster. The rule for selecting nodes for the EA Factors cluster and the EF Factors cluster of the simplified env.Plan model is whether the absolute value of *EI* is 8. In other words, all factors with a EI value of −8 go to EA cluster, and all factors with a EI of +8 go to EF cluster; all other factors are therefore ignored for the simplified env.Plan model. According to the computation results in the synthesized supermatrix for the simplified env.Plan model, $w_{C_{\text{Plan}},i} = (0.110243, 0.036108, 0.042977)$, so $W_i = (0.58229, 0.19072, 0.22700)$, so Plan A is also selected.

Interestingly, both complicated env.Plan model and simplified env.Plan model led to the same conclusion that Plan A is the best environmental-conscious construction plan. Besides the selected plan, it is also noticed that priority queues of these plan alternatives are also equivalent (refer to Table 3.13). Considering the load of performing pairwise comparisons on the clusters and nodes would be

Table 3.13 A comparison between the two env.Plan models using priority weight

ANP model	*No. of nodes*	*Synthesized priority weight W_i*			*Selected plan*
		Plan A	*Plan B*	*Plan C*	
Simplified model	15	0.58229	0.19072	0.22700	Plan A
Complicated model	35	0.59351	0.21926	0.18723	Plan A

multiplied many times in a complicated env.Plan model, the simplified env.Plan model appears to be more practicable and efficient.

According to the attributes of plan alternatives listed in Table 3.8, the comparison results using W_i also imply that the most preferable plan for environmental-conscious construction is the plan that regulates the construction practice with least consumption on fuel and water, a lowest ratio of wastage, and a maximum ratio of recycle and re-use on materials and packaging, etc. This indicates the env.Plan method can provide a quite reasonable comparison result for environmental-conscious construction and thus can be applied into construction practice.

3.3.4 Recommendations

In summary, in order to apply the env.Plan model in practice, the following steps are recommended:

1. selection of an ANP model between the simplified env.Plan model and the complicated env.Plan model;
2. original assessment of plan alternatives based on all environmental indicators, using Table 3.8;
3. pairwise comparisons among all environmental indicators using Table 3.9;
4. supermatrix calculation following the three substeps to transform an initial supermatrix to a limiting supermatrix with reference to Tables 3.11 and 3.12;
5. calculation of limiting priority weight of each plan alternative using limiting supermatrix and decision-making on plan alternatives using Table 3.13;
6. if none of the plan alternatives meets environmental requirements, adjustments to the plans are needed and re-evaluation of the plans by repeating the procedure from step 2.

3.4 An ANP model for demolition planning[1]

3.4.1 Background

Demolition is an activity to disassemble and destroy a building or parts of a building for reconstruction or renovation. In general, the demolition procedure can be

1 A collaborative research with Professor Chimay Anumba and Dr Arham Abdullah.

divided into four main stages (BSI 2000; Abdullah and Anumba 2002a,b): tendering stage, pre-demolition stage, actual demolition stage, and post-demolition stage. Because demolition is regarded as a reversed process of construction (Miller 1999) demolition contractors usually use similar management methods in their projects. For example, demolition planning, just like construction planning, is also conducted at the tendering stage. Moreover, the technical aspects considered in construction planning, such as techniques, resources, duration, and site layout (Hendrickson and Au 2000), are involved in demolition planning also.

In order to select the best demolition plan for a demolition project, Kasai (1998) suggested that there are 8 criteria including structural form of the building, location of the building, permitted level of nuisance, scope of demolition, use of building, safety, and demolition period, etc. On the other hand, Abdullah and Anumba (2002a,b) developed an AHP model with six criteria: structure characteristics, site conditions, demolition cost, past experience, time, and re-use and recycling. And their case studies indicated that the AHP model could effectively help demolition contractors to select appropriate techniques for their demolition projects. Moreover, both of the two research works concluded that the decision-makers of demolition planning have to keep in mind that health and safety are the main concerns in the selection process, and the selection of the most appropriate demolition technique could be subject to a unique combination of these criteria.

Previous research has proven the usefulness of AHP in selecting the most appropriate demolition technique for any given demolition project during the planning stage. However, the calculation results in an AHP model where interrelationships among clusters are ignored may be different if the interrelationships among the clusters are considered. For example, besides the influence on the final decision on the selection of best demolition technique, the structure characteristics can also influence other clusters in the AHP model, such as cost, time, and re-use and recycling (Abdullah and Anumba 2002a,b). In fact, this problem can be solved by using ANP, which is a natural generalization and extension of the AHP that allows feedback and dependence among decision elements and clusters of elements (Saaty 1996). In this section, the authors introduce an ANP model (named DEMAN) using the same criteria and subcriteria, which are transplanted from the AHP model (named DEMAP) developed in previous research works by Abdullah and Anumba (2002a,b) and Anumba *et al.* (2003). And a comparison of the calculation results between DEMAP and DEMAN is then made.

3.4.2 Statement of problem

3.4.2.1 Demolition planning

Demolition planning is an essential and necessary activity in the management and execution of demolition projects. It is usually conducted with several technical aspects corresponding to what are normally involved in construction planning, such as the choice of demolition techniques and plans. As an essential and challenging task, demolition planning has to not only strive to meet common concerns such as time, cost, and safety requirement, but also explore possible measures to minimize adverse environmental impacts of the demolition projects at the outset.

3.4.2.2 Evaluation criteria

In order to evaluate the advantage in different demolition plan alternatives, the authors use the same evaluation criteria that have been developed for best demolition technique selection in previous researches (Abudayyeh *et al.* 1998; Fesseha 1999; Abdullah and Anumba 2002a,b; Anumba *et al.* 2003), as the contents of the demolition technique evaluation and the demolition plan evaluation are similar. Thus, there are 6 main criteria and a total of 17 sub-criteria transplanted (see Section 3.4.3.1) for the selection of best demolition plan, and all these evaluation criteria are described in Table 3.14 (Abdullah and Anumba 2002a,b).

3.4.2.3 A demonstration project

In order to compare the calculation results from the AHP and the ANP, the authors transplant criteria from previous studies into one demonstration demolition project. Table 3.14 illustrates characteristics of three demolition plan alternatives in the demonstration project based on the criteria. The three demolition plan alternatives are the plan using progressive demolition method (DTPM plan), the plan using deliberate collapse mechanism method (DTAM plan), and the plan using deconstruction method (DTDM). Regarding the criteria adopted, this comparative study does not include characteristics other than these 17 variables (refer to Table 3.14), which are also potential criteria for the evaluation of demolition plans.

3.4.3 Methodology

The methodology adopted in this research is the transplantation of evaluation criteria from previous studies on the selection of best demolition technique, the construction of an ANP model using the evaluation criteria, and comparison between the calculation results from the proposed MCDM models.

3.4.3.1 Transplantation of evaluation criteria

As mentioned in Section 3.4.2, the evaluation criteria developed for selecting the best demolition technique consist of 6 main criteria and 17 sub-criteria from previous research (Abdullah and Anumba 2002a,b; Anumba *et al.* 2003). The transplantation of these evaluation criteria from the selection of demolition

Table 3.14 Indicators and their corresponding values of plan alternatives for the AHP/ANP model

Classification (cluster)	*Technique indicator (Node)*	*Unit*	*Plan alternatives*		
			DTPM[a]	DTAM[a]	DTDM[a]
Structure characteristics (SCH)	Height (SCHH)	Storey	12	12	12
	Type (SCHT)	–	PRCS[b]	PRCS[b]	PRCS[b]
	Stability (SCHS)	–	Stable	Stable	Stable
	Degree/Extent of demolition (SCHD)	–	Full	Full	Full
	Use of the structure (SCHU)	–	Housing	Housing	Housing
Site conditions (SCD)	Health and safety for the person on/off site (SCDH)	–	Medium	Low	High
	Acceptable level of noise (SCDN)	dB(A)	70–74	70–74	70–74
	Proximity of the adjacent structures (SCDP)	Meter	50	50	50
	Site accessibility (SCDA)	–	Accessible	Accessible	Accessible
Cost (DTC)	Machinery (DTCE) (Lump sum)	£	50,000	30,000	50,000
	Manpower (DTCW) (Lump sum)	£	65,000	70,000	75,000
Past experiences (PED)	Familiarity with a specified technique (PEDS)	–	Familiar	Familiar	Unfamiliar
	Availability of plant and equipment (PEDP)	–	Available	Available	Available
	Availability of expertise (PEDE)	–	Available	Available	Available
Re-use and recycling (DTR)	Level of re-use and recycling (DTRL)	–	Moderate	Moderate	Moderate
Time (DTT)	Site preparation (DTTP)	Month	3	3	3
	Actual demolition (DTTD)	Month	3	3	3

Notes

a DTPM acts as progressive demolition plan, DTAM acts as deliberate collapse mechanism plan, and DTDM acts as deconstruction plan.

b PRCS acts as precast reinforced concrete structure.

techniques to the selection of demolition plan requires verification of transplantation alternatives and assumptions on account of the relative uniformity and difference between the selection of demolition techniques and the selection of demolition plans. In this section, after a comparative study of the two kinds of selection, the authors finally chose an intact transplantation of the evaluation criteria from the developed model for selecting the best demolition technique.

3.4.3.2 Selection of ANP

The ANP is more powerful in modelling complex decision environments than the AHP because it can be used to model very sophisticated decisions involving a variety of interactions and dependencies (Meade and Sarkis 1999; Saaty 1999). The ANP is a natural generalization and extension of the AHP that allows feedback and dependence among decision elements and clusters of elements. It is also a general theory of relative measurement used to derive composite priority ratio scales from individual ratio scales that represent relative measurements of the influence of elements that interact with respect to control criteria (Saaty 1996, 1999). All these advantages are embodied in several examples of applications of the ANP (Srisoepardani 1996). For example, Meade and Sarkis (1999) applied the ANP to the strategic evaluations of environmental practices and programmes in both manufacturing and business to help analyse various project-, technological- or business-decision alternatives. Therefore, Saaty (1996) recommended the ANP be used for cases where the most thorough and systematic analysis of influences needs to be made.

3.4.4 DEMAN model

3.4.4.1 Model construction

This section aims to construct an ANP model for selecting the best demolition plan based on the determined control hierarchy components used in the DEMAP model: structure characteristics, site condition, costs, past experience, environmental protection, and time. Meanwhile, the corresponding criteria for comparing these components (clusters) and sub-criteria for comparing the elements (nodes) of these components of the DEMAP system will be employed to compare the DEMAN model with the DEMAP model. According to the definition given by Saaty (1996), a cluster is connected to another cluster when at least one element in it is connected to at least one element in another cluster. Moreover, a determination of the clusters with their nodes for each control criterion or sub-criterion will also be done for the final comparison. The DEMAN model is outlined in Figure 3.11.

The DEMAN environment includes exterior environment and interior environment. In the exterior DEMAN environment, the downward arrow indicates the

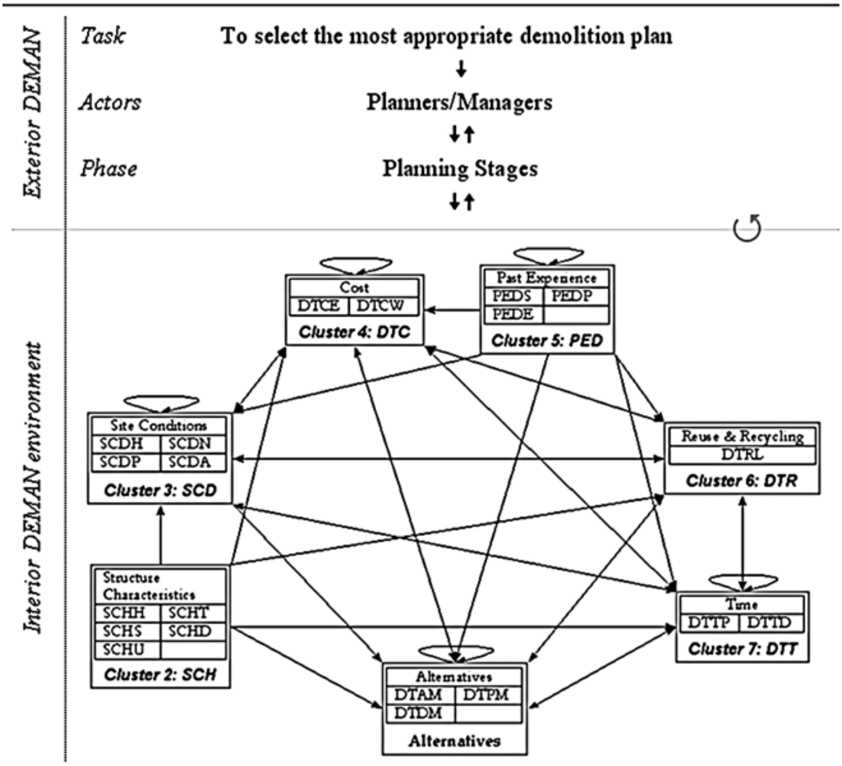


Figure 3.11 The ANP environment for demolition plan selection.

process of transferring data required by the DEMAN, while the upward arrow indicates the process of feedback with evaluation results from the DEMAN. On the other hand, the feedback process (loop) (denoted by ↺) between the exterior environment and the interior environment indicates a circulating process for the selection of alternative demolition technique plans. In the interior DEMAN environment, connections among 7 clusters and 20 nodes are modelled by two-way and looped arrows to describe the existing interdependencies. The 7 clusters are demolition technique plan alternatives (DTA), structure characteristics (SCH), site conditions (SCD), cost (DTC), past experience (PED), re-use and recycling (DTR), and time (DTT). In correspondence with these 7 clusters, there are 20 nodes: 3 nodes in DTA, 5 nodes in SCH, 4 nodes in SCD, 2 nodes in DTC, 3 nodes in PED, 1 node in DTR, and 2 nodes in DTT. All these clusters and nodes are also described in Table 3.14. Figure 3.11 illustrates the DEMAN model implemented using an ANP with all interior clusters and nodes, and exterior-related participators.

3.4.4.2 *Pairwise comparisons*

Concerning the interdependencies between any two clusters and any two nodes, the pairwise comparisons between clusters, as well as pairwise comparisons between nodes are performed as they are interdependent. On completing the pairwise comparisons, the relative importance weight (denoted as a_{ij}) of interdependence is determined by using a scale of pairwise judgement, where the relative importance weight is valued from 1 to 9 (Saaty 1996). The fundamental scale of pairwise judgement is given in Table 3.15.

Table 3.15 gives a general form for pairwise judgements between any two clusters and between any two nodes in the DEMAN model. The relative importance weight of interdependence is determined manually to reflect professional experience and knowledge in the application area. In this study, the authors determine it, as the objective of this study is mainly to demonstrate the usefulness of the ANP model in selecting the best demolition plan. For example, the

Table 3.15 Pairwise judgements between clusters/nodes in the DEMAN model

Clusters/Nodes		*Pairwise judgements*									
		±1	±2	±3	±4	±5	±6	±7	±8	±9	Scales of pairwise judgements (Saaty, 1996)
Cluster *I*	Cluster *J*	**x**	**x**	**x**	**x**	**x**	✓	**x**	**x**	**x**	1 = Equal,
Node I_i	Node J_j	**x**	**x**	**x**	**x**	**x**	✓	**x**	**x**	**x**	2 = Equally to moderately dominant, 3 = Moderately dominant, 4 = Moderately to strongly dominant, 5 = Strongly dominant, 6 = Strongly to very strongly dominant, 7 = Very strongly dominant, 8 = Very strongly to extremely dominant, 9 = Extremely dominant.

Notes

1 The symbol **x** denotes item under selection for pairwise judgement, and the symbol ✓ denotes selected pairwise judgement.

2 *I* and *J* denote the number of clusters, whilst *i* and *j* denote the total number of nodes.

3 The symbol ± denotes importance initiative between compared nodes or clusters.

relative importance weights among cluster 2 to 7 are the same as what they are in the DEMAN model (refer to Table 3.15), and the relative importance weights between cluster 1 and any one of the other six clusters are set as 1. On the other hand, the relative importance weights between any two nodes, which have a potential interdependence relationship, are set up based on the quantitative or qualitative attribute of each node in the demolition plan which has been given in Table 3.14. As a result, all pairwise comparisons between any two clusters and between any two nodes are defined according to their potential relationship based on the given scale of pairwise judgements.

Weights for all interdependencies of a particular demolition plan are then aggregated into a series of submatrices. For example, provided that the cluster of plan alternatives (DTA) includes DTAM, DTPM and DTDM, and each of these plan alternatives is connected to nodes in the cluster of cost (DTC), pairwise judgements of the cluster result in relative weights of importance between each plan alternative and each cost factor. The aggregation of the weights thus forms a 3×2 submatrix located at W_{41} in Table 3.16. It is necessary to note that pairwise comparisons are necessary to all potential connections between clusters and between nodes in the DEMAN model to identify the level of interdependencies which are fundamental in the ANP procedure. The series of submatrices are then aggregated into a supermatrix, which is denoted as supermatrix A in this study, and it will be used to derive the initial supermatrix in later calculations.

3.4.4.3 Supermatrix calculation

The supermatrix of the DEMAN system is a two-dimensional partitioned matrix consisting of 49 submatrices (refer to Table 3.16). The calculation of supermatrix aims to form a synthesized supermatrix to allow for the resolution of the effects of the interdependencies that exist between the nodes and the clusters of the ANP model. In order to obtain useful information for demolition plan selection, the

Table 3.16 Formulation of supermatrix and its submatrix for the DEMAN

Supermatrix	Submatrix
$W = \begin{bmatrix} W_{11} & W_{12} & \cdots & W_{17} \\ W_{21} & W_{22} & \cdots & W_{27} \\ \cdots & \cdots & \cdots & \cdots \\ W_{71} & W_{72} & \cdots & W_{77} \end{bmatrix}$ $Cluster: \; C_1 \quad C_2 \quad \cdots \quad C_7$ $Node: \; N_{1_{1\sim3}} N_{2_{15}} \quad \cdots \quad N_{7_{1\sim2}}$	$W_{IJ} = \begin{bmatrix} w_1\|_{I,J} & \cdots & w_1\|_{I,J} \\ w_2\|_{I,J} & \cdots & w_2\|_{I,J} \\ \cdots & \cdots & \cdots \\ w_i\|_{I,J} & \cdots & w_i\|_{I,J} \\ \cdots & \cdots & \cdots \\ w_{N_{I_1}}\|_{I,J} & \cdots & w_{N_{I_n}}\|_{I,J} \end{bmatrix}$

Notes

I is the index number of rows; and J is the index number of columns; both I and J correspond to the number of clusters and their nodes ($I, J \in (1, 2, \ldots, 20)$), N_I is the total number of nodes in cluster I, n is the total number of columns in cluster I. Thus a 20×20 supermatrix is formed.

calculation of supermatrix is to be done following three steps which transform an initial supermatrix to a weighted supermatrix, and then to a synthesized supermatrix.

At first, an initial supermatrix of the DEMAN model is created. The initial supermatrix consists of local priority vectors obtained from the pairwise comparisons among clusters and nodes. A local priority vector is an array of weight priorities containing a single column (denoted as $w^T = (w_1, w_2, \ldots, w_i, \ldots, w_n)$), whose components (denoted as w_i) are derived from a judgement comparison matrix A and deduced by Equation 3.8 in Section 3.3.3.3. The initial supermatrix is constructed by substituting the submatrices into the supermatrix as indicated in Table 3.16. A detail of the initial supermatrix is given in Table 3.17.

After the formation of the initial supermatrix, it is transformed into a weighted supermatrix by multiplying every node in a cluster of the initial supermatrix by the weight of the cluster, which has been established by pairwise comparison among the seven clusters. In the weighted supermatrix, each column is stochastic, i.e. sum of a column amounts to 1 (Saaty 2001) (refer to Table 3.17).

The last step is to compose a limiting supermatrix, which is to raise the weighted supermatrix to powers until it converges/stabilizes, i.e. when all the columns in the supermatrix have the same values. Saaty (1996) indicated that as long as the weighted supermatrix is stochastic, a meaningful limiting result could be obtained for prediction. The approach to arrive at a limiting supermatrix is by taking repeatedly the power of the matrix, i.e. the original weighted supermatrix, its square, its cube, etc., until the limit is attained (converges), in which case all the numbers in each row will become identical. Calculus-type algorithm is employed in the software environment of Super Decisions, designed by Bill Adams and the Creative Decision Foundation, to facilitate the formation of the limiting supermatrix, and the calculation result is listed in Table 3.17.

3.4.4.4 Demolition plan selection

The selection aims to choose the best demolition plan based on the computation results of the limiting supermatrix of the ANP model. Main results of the ANP model computations are the overall priorities of the alternatives obtained by synthesizing the priorities of individual demolition plans against different technique indicators (nodes). The selection of the best demolition plan, which has the highest priority for technological advantage, can be done using a limiting priority weight, which is defined in Equation 3.9 in Section 3.3.3.4. For the specified decision-making problem, W_i is the synthesized priority weight of plan alternative $i (i = 1, \ldots, n)$ (n is the total number of demolition plan alternatives, $n = 3$ in this study), and $w_{C_{\text{Plan}},i}$ is the limited weight of demolition plan alternative i in the limiting supermatrix. Because the $w_{C_{\text{Plan}},i}$ is transformed from pairwise judgements, it is reasonable to regard it as the priority of the plan alternative i and thus to be used in Equation 3.9. According to the computation results in the

Table 3.17 The supermatrix for the DEMAN

Initial supermatrix

Nodes	*DTAM*	*DTPM*	*DTDM*	*SCHH*	*SCHT*	*SCHS*	*SCHD*	*SCHU*	*SCDH*	*SCDN*	*SCDP*	*SCDA*	*DTCE*	*DTCW*	*PEDS*	*PEDP*	*PEDE*	*DTRL*	*DTTP*	*DTTD*
DTAM	0.00000	0.50000	0.50000	0.33333	0.33333	0.33333	0.33333	0.33333	0.68542	0.33333	0.33333	0.33333	0.71429	0.28083	0.46154	0.33333	0.33333	0.33333	0.33333	0.33333
DTPM	0.50000	0.00000	0.50000	0.33333	0.33333	0.33333	0.33333	0.33333	0.23441	0.33333	0.33333	0.33333	0.14286	0.58415	0.46154	0.33333	0.33333	0.33333	0.33333	0.33333
DTDM	0.50000	0.50000	0.00000	0.33333	0.33333	0.33333	0.33333	0.33333	0.08017	0.33333	0.33333	0.33333	0.14286	0.13501	0.07692	0.33333	0.33333	0.33333	0.33333	0.33333
SCHH	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCHT	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCHS	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCHD	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCHU	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCDH	0.00000	0.00000	0.00000	0.67259	0.64686	0.66282	0.65559	0.66220	0.00000	0.75000	0.75000	0.75000	0.66220	0.66220	0.66220	0.66220	0.66220	0.66220	0.66220	0.66046
SCDN	0.00000	0.00000	0.00000	0.07588	0.10047	0.08072	0.11069	0.15531	0.50000	0.00000	0.12500	0.12500	0.07843	0.07843	0.07843	0.07843	0.07843	0.07843	0.07843	0.07448
SCDP	0.00000	0.00000	0.00000	0.11969	0.09786	0.12607	0.09779	0.09124	0.25000	0.12500	0.00000	0.12500	0.12968	0.12968	0.12968	0.12968	0.12968	0.12968	0.12968	0.12831
SCDA	0.00000	0.00000	0.00000	0.13184	0.15481	0.13039	0.13592	0.09124	0.25000	0.12500	0.12500	0.00000	0.12968	0.12968	0.12968	0.12968	0.12968	0.12968	0.12968	0.13675
DTCE	0.25000	0.11111	0.14286	0.83333	0.73850	0.50000	0.50000	0.50000	0.50000	0.50000	0.50000	0.50000	0.00000	1.00000	0.50000	0.50000	0.50000	0.50000	0.50000	0.50000
DTCW	0.75000	0.88889	0.85714	0.16667	0.26150	0.50000	0.50000	0.50000	0.50000	0.50000	0.50000	0.50000	1.00000	0.00000	0.50000	0.50000	0.50000	0.50000	0.50000	0.50000
PEDS	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.50000	0.50000	0.00000	0.00000	0.00000
PEDP	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.50000	0.00000	0.50000	0.00000	0.00000	0.00000
PEDE	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.50000	0.50000	0.00000	0.00000	0.00000	0.00000
DTRL	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
DTTP	0.50000	0.50000	0.50000	0.50000	0.58247	0.56868	0.50000	0.50000	0.50000	0.50000	0.56213	0.50000	0.50000	0.50000	0.50000	0.50000	0.50000	0.50000	0.00000	0.10000
DTTD	0.50000	0.50000	0.50000	0.50000	0.41753	0.43133	0.50000	0.50000	0.50000	0.50000	0.43787	0.50000	0.50000	0.50000	0.50000	0.50000	0.50000	0.50000	1.00000	0.00000

Weighted supermatrix

Nodes	*DTAM*	*DTPM*	*DTDM*	*SCHH*	*SCHT*	*SCHS*	*SCHD*	*SCHU*	*SCDH*	*SCDN*	*SCDP*	*SCDA*	*DTCE*	*DTCW*	*PEDS*	*PEDP*	*PEDE*	*DTRL*	*DTTP*	*DTTD*
DTAM	0.00000	0.17987	0.17987	0.07754	0.07754	0.07754	0.07754	0.07754	0.17205	0.08367	0.08367	0.08367	0.26617	0.10465	0.11464	0.08279	0.08279	0.09926	0.10634	0.10634
DTPM	0.17987	0.00000	0.17987	0.07754	0.07754	0.07754	0.07754	0.07754	0.05884	0.08367	0.08367	0.08367	0.05323	0.21768	0.10464	0.08279	0.08279	0.09926	0.10634	0.10634
DTDM	0.17987	0.17987	0.00000	0.07754	0.07754	0.07754	0.07754	0.07754	0.02012	0.08367	0.08367	0.08367	0.05323	0.05031	0.01911	0.08279	0.08279	0.09926	0.10634	0.10634
SCHH	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCHT	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCHS	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCHD	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCHU	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCDH	0.00000	0.00000	0.00000	0.04446	0.04276	0.04382	0.04334	0.04378	0.00000	0.05565	0.05565	0.05565	0.10022	0.10022	0.10371	0.10371	0.10371	0.17058	0.12259	0.12227
SCDN	0.00000	0.00000	0.00000	0.00502	0.00664	0.00534	0.00732	0.01027	0.03710	0.00000	0.00928	0.00928	0.01187	0.01187	0.01228	0.01228	0.01228	0.02020	0.01452	0.01379

SCDP	0.00000	0.00000	0.00000	0.00791	0.00647	0.00833	0.00647	0.00603	0.01855	0.00928	0.00000	0.00928	0.01963	0.01963	0.02031	0.02031	0.02031	0.03341	0.02401	0.02375
SCDA	0.00000	0.00000	0.00000	0.00872	0.01023	0.00862	0.00898	0.00603	0.01855	0.00928	0.00928	0.00000	0.01963	0.01963	0.02031	0.02031	0.02031	0.03341	0.02401	0.02532
DTCE	0.03867	0.01719	0.02210	0.14283	0.12658	0.08570	0.08570	0.08570	0.08548	0.08548	0.08548	0.08548	0.00000	0.00040	0.05586	0.05586	0.05586	0.12247	0.07603	0.07603
DTCW	0.11601	0.13749	0.13258	0.02857	0.04482	0.08570	0.08570	0.08570	0.08548	0.08548	0.08548	0.08548	0.00040	0.00000	0.05586	0.05586	0.05586	0.12247	0.07603	0.07603
PEDS	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.10973	0.10973	0.00000	0.00000	0.00000
PEDP	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.10973	0.00000	0.10973	0.00000	0.00000	0.00000
PEDE	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.10973	0.10973	0.00000	0.00000	0.00000	0.00000
DTRL	0.30446	0.30446	0.30446	0.32196	0.32196	0.32196	0.32196	0.32196	0.30905	0.30905	0.30905	0.30905	0.00040	0.00040	0.15212	0.15212	0.15212	0.00000	0.13719	0.13719
DTTP	0.09056	0.09056	0.09056	0.10396	0.12111	0.11824	0.10396	0.10396	0.09739	0.09739	0.10949	0.09739	0.23761	0.23761	0.05586	0.05586	0.05586	0.09985	0.00000	0.20661
DTTD	0.09056	0.09056	0.09056	0.10396	0.08681	0.08968	0.10396	0.10396	0.09739	0.09739	0.08529	0.09739	0.23761	0.23761	0.05586	0.05586	0.05586	0.09985	0.20661	0.00000

Limiting supermatrix

Nodes	*DTAM*	*DTPM*	*DTDM*	*SCHH*	*SCHT*	*SCHS*	*SCHD*	*SCHU*	*SCDH*	*SCDN*	*SCDP*	*SCDA*	*DTCE*	*DTCW*	*PEDS*	*PEDP*	*PEDE*	*DTRL*	*DTTP*	*DTTD*
DTAM	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059	0.12059
DTPM	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174	0.11174
DTDM	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638	0.09638
SCHH	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCHT	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCHS	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCHD	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCHU	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SCDH	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495	0.07495
SCDN	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159	0.01159
SCDP	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583	0.01583
SCDA	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601	0.01601
DTCE	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748	0.05748
DTCW	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088	0.09088
PEDS	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
PEDP	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
PEDE	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
DTRL	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904	0.16904
DTTP	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792	0.11792
DTTD	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760	0.11760

limiting supermatrix in Table 3.17, $w_{C_{\text{Plan}},i} = (0.120594, 0.111735, 0.096383)$, so $W_i = (0.366867, 0.339917, 0.293216)$; as a result, the best demolition plan is DTAM.

3.4.5 Comparison between DEMAP and DEMAN

Both DEMAP and DEMAN provided the same conclusion that the demolition plan using DTAM is the best demolition plan. Besides the selected demolition plan, it is also noticed that priority queues of these three demolition plan alternatives are also equivalent (refer to Table 3.18).

The comparison result implies that the most preferable demolition plan regulates the demolition practice with the least requirement on machinery, and the lowest risk ratios of health and safety for people on and off site, because of the attributes of demolition plan alternatives listed in Table 3.14. This result also indicates both DEMAP and DEMAN can provide a quite reasonable comparison result for environmental-conscious demolition.

Although the DEMAN appears to provide a more precise result than the DEMAP due to its load of performing pairwise comparisons between clusters and between nodes, the difference between priority weights of DTAM and DTPM in the DEMAN is not as absolutely clear as those in the DEMAP. There are two possible explanations for this result. One explanation is that there is a risk of getting results which provide unrealistic rankings when ANP is applied comparing with the results from AHP (Salomon and Montevechi 2001). On the contrary, another explanation is that the difference of advantages between DTAM and DTPM is not significant indeed. For example, there is difference between DTAM and DTPM in three attributes: the SCDH, DTCE, and DTCW (refer to Table 3.14). Because the DTAM is preferable to DTPM in SCDH and DTCE, and is inferior to DTPM in DTCW, there is no absolute advantage in DTAM; and the authors prefer to agree to the second explanation. However, in order to prove that the DEMAN can provide a more precise result than the DEMAP, the authors suggest further case studies other than the demonstration project used in this study.

Moreover, according to the calculation results of priority weight (refer to Table 3.18), it is also noticed that there is no demolition plan with a priority weight over 0.5 in the two MCDM models. There are also two possible reasons.

Table 3.18 A comparison between two MCDM models using priority weight

MCDM model	*No. of nodes*	Synthesized priority weight			*Selection*
		DTAM plan	*DTPM plan*	*DTDM plan*	
DEMAP	17	0.490	0.318	0.192	DTAM plan
DEMAN	20	0.367	0.340	0.293	DTAM plan

One possible reason is that none of these three demolition plans has significant advantage over others in this demonstration project, whilst another possible reason is that the evaluation criteria used in the DEMAP and the DEMAN cannot significantly distinguish these three demolition techniques by using the attributes defined. As a result, further researches will focus on the evaluation of the two MCDM models in different demolition projects and modification of the evaluation criteria used in the two MCDM models.

3.4.6 Summary

There are two contributions in this section. The first one is that the authors successfully transplant the intact evaluation criteria of selecting the best demolition technique into both DEMAP model and DEMAN model, and another one is that the authors make a comparison between the two MCDM models by using a case from a demonstration project. Although the evaluation criteria of selecting the best demolition technique can be transplanted in the DEMAP model and the DEMAN model, and both of these two MCDM models can work well for selecting the best demolition plan, there are also some problems. For example, no priority weight of a demolition plan is over 0.5 according to the calculation results, and the differences of priority weight among plan alternatives are small, especially for the DEMAN model. The authors also discussed the possible reasons related to these problems and the direction of further research.

3.5 Conclusions and discussions

A quantitative approach to construction pollution management by introducing parameters of CPI and pollution and hazard magnitude h_i has been proposed. By using these parameters, a method to predict the distribution of accumulated pollution level generated from construction operations is presented. It is suggested that if the pollution level exceeds the allowable limit, then construction activities need to be re-scheduled to "spread" the polluting emissions. In doing so, polluting emission is treated as a pseudo resource, and then applied to a GA-based levelling technique to re-schedule the project activities. The GA allows the user to concurrently minimize fluctuations and period of resource use by assigning different priorities to project activities. Experimental results indicate that GA-enhanced resource levelling performs better than the traditional resource levelling method used in Microsoft Project©.

As a matter of fact, the proposed method for controlling construction pollution is an effective tool that can be used by project managers to reduce the level of pollution generated from a project at a certain period of time. This method is useful when there is no other way to reduce the level of pollution. However, it is necessary to point out that the method proposed here can only redistribute the amount of pollution over project duration so that at any specific period of time, the level of pollution will not exceed the legal limit. In order to reduce the overall amount of pollution, other methods, such as alternative construction technologies and new materials, have to be applied.

This chapter also presents an env.Plan method for environmental-conscious construction planning when plan alternatives need to be selected for reducing adverse environmental impacts in construction, especially after CPI levelling. The env.Plan method was constructed and illustrated using ANP, and both simplified env.Plan model and complicated env.Plan model are developed. The simplified model consists of 4 clusters and 15 corresponding nodes, while the complicated model consists of 4 clusters and 35 corresponding nodes. In addition, performances of the two models are compared and the results indicated that while the complicated model yielded accurate results, the simplified model is easy to use.

The env.Plan method is put forward based on an ANP model which contains feedback and self-loops among the clusters (refer to Figure 3.10), but no control structure. However, there is an implicit control criterion with respect to which all judgements are made in the env.Plan model: environmental impact. The supermatrix computations are conducted for the overall priorities of plan alternatives, which are obtained by synthesizing the priorities of the alternatives from all the subnetworks of the ANP model. Finally, the synthesized priority weight W_i is used to distinguish the degree of potential environmental impacts due to the implementation of a construction plan.

However, problems also exist in the env.Plan method; for example, the reliability of the three clusters – EA Factors (C_2), EU Factors (C_3) and EF Factors (C_4) – and their nodes cannot be measured. As the sorting criteria rely on the calculation results of the EI_i, subjective judgements can influence the accuracy of the system. Further studies are therefore needed to investigate these issues.

The ANP is employed here to realize the purpose of demolition plan selection. It is concluded that the ANP is a viable and capable tool for selecting the best demolition plan by using the same set of evaluation criteria transplanted from the AHP model developed in previous research. However, although the ANP has the ability to measure relationships among selection criteria and their subcriteria, which is normally ignored in the AHP, the authors also conclude that it should be examined if the ANP model can provide a more accurate result in further research.

Chapter 4

Effective control at construction stage

4.1 Introduction

Construction waste is a serious environmental problem in many large cities. According to statistical data, C&D debris frequently makes up 10–30 percent of the waste received at many landfill sites around the world (Fishbein 1998). However, in Hong Kong, an average of 7,030 tons of C&D waste were disposed of at landfills everyday in 1998, representing about 42% of total waste intake at landfills, and most of which can be reclaimed; and in 1999, there were 7890 tons of C&D waste disposed of at landfills every day, representing about 44% of total waste intake at landfills (HKEPD 1999a,b,c,d, 2000a,b,c,d). In contrast to the percentage in other advanced countries, for example, C&D debris makes up only 12% of the waste received at Metro Park East Sanitary Landfill of Iowa State in the United States (MWA 2000); the quantity of C&D waste in Hong Kong is much higher. As there are increasing demands on residential buildings in Hong Kong, a 13-year production program had been established by the Hong Kong SAR government in 1998, which has been rolled forward to produce an average of 50,000 flats in the public sector and 35,000 flats in the private sector each year (HB 2000). So how to reduce construction waste is becoming more important in Hong Kong.

There have been many research efforts for construction waste control in Hong Kong. For example, a study that investigated construction waste generated from public housing projects in Hong Kong was conducted in 1992 (Cheung *et al.* 1993). Methods for construction waste minimization in Hong Kong were also discussed by (Poon *et al.* 1996). These waste minimization methods emphasize the use of modern technologies in building construction, such as precast concrete, steel form and scaffold, drywall partition panel, etc. However, surveys show that local construction firms in Hong Kong feel it is expensive to use new machinery and automation (Ho 1997); most (68–85%) local construction firms agree to adopt low-waste techniques only when they are demanded by the designers, the specifications, or the clients (Poon and Ng 1999). As a result, construction waste control in Hong Kong is still a major problem to be solved.

Previous practice and studies have established a set of waste prevention strategies considered in building construction. These strategies mainly involve the effective coordination of materials management, including efficient purchase and ordering of materials; efficient timing and delivery; efficient storage; and the use of materials to minimize loss, maximize re-use, prevent undoing and redoing, and reduce packaging waste, etc. (Fishbein 1998). The management of on-site waste is thus emphasized on executing a waste management plan for each construction and demolition site (Coventry *et al.* 1999). As another important factor, design coordination has a major impact on waste generation. Incorrect or unconstructable designs result in significant amounts of wastes. A study on the relationship between causes and costs of rework indicates that, among other factors, design coordination is predominantly important (Love and Li 2000). However, as the housing projects in Hong Kong adopt a series of standard designs developed by the Housing Authority of the Hong Kong SAR, the effect of design coordination is minimized, if not negligible. Therefore, in this study, the impact of design coordination on waste generation is not considered.

The objective of this chapter is to present an on-site material management scheme using an incentive reward program (IRP) to control and reduce construction wastes. The scheme is designed to encourage construction workers, who are directly involved in producing construction wastes, to reduce wastes by rewarding them based on the amounts and values of the materials they saved. The bar-coding technique is used to facilitate easy data recording and transfer.

4.2 Generation of construction wastes

Although there is no generally accepted definition, construction waste can be loosely defined as the debris of C&D (U.S.EPA 2000). Specifically, construction waste refers to solid waste containing no liquids and hazardous substances, largely inert waste, resulting from the process of construction of structures, including buildings of all types (both residential and nonresidential) as well as roads and bridges. Construction waste does not include clean-up materials contaminated with hazardous substances, friable asbestos-containing materials, lead, waste paints, solvents, sealers, adhesives, living garbage, furniture, appliances, or similar materials.

Although it is difficult to give exact figures of construction wastes generated on a construction site, it is estimated that as much as 10–30% construction materials are wasted (Stone 1983; Fishbein 1998). Data obtained from specialty contractors in USA, UK, mainland China, Hong Kong, Brazil, and Korea present a comparison of construction wastes generated from construction industries in these countries/regions, which is displayed in Table 4.1.

The authors conducted a construction waste survey, in which an on-the-spot investigation about construction waste generation in residential projects in Hong Kong is planned, and we aim to put forward a reasonable scheme to solve the problem of construction waste generation. In our construction site study, both major contractors and clients are selected on account of their technologies and projects that are widely representative in the Hong Kong construction industry. The contractors are Yau Lee Construction Co., Ltd and Hung Hom Construction Co., Ltd; and the clients are the Hong Kong Housing Authority and Sun Hung Kai

Table 4.1 Average on-site wastage rate of construction materials

Material	*Average wastage (%)*					
	USA	*UK*	*Mainland China*	*Hong Kong*	*Brazil*	*Seoul*
Brick/Block	3.5	4.5	2.0	N/A	17.5	3.0
Concrete	7.5	2.5	2.5	6.7	7.0	1.5
Drywall	7.5	5.0	N/S	9.0	N/S	N/S
Formwork	10.0	N/S	7.5	4.6	N/S	16.7
Glass	N/S	N/S	0.8	2.3	N/S	6.0
Mortar	3.5	N/S	5.0	3.2	46.0	0.3
Nail	5.0	N/S	N/S	N/A	N/S	N/S
Rebar	5.0	N/S	3.0	8.0	21.0	N/S
Tile	6.5	5.0	N/S	6.3	8.0	2.5
Wallpaper	10.0	N/S	N/S	N/A	N/S	11.0
Wood	16.5	6.0	N/S	45.0	32.0	13.0

Notes
1 N/S = Not specified, N/A = Not available;
2 Reference: USA (Schuette and Liska 1994), UK (Skoyles 1992; Frics 1996); Mainland China (Zhu 1996), Hong Kong (Site surveys), Brazil (Bossink and Brouwers 1996), and Seoul (Seo and Hwang 1999).

Properties Co., Ltd. Two representative public housing projects and one private housing project are selected for the survey. Of the two public housing projects, one is a public housing project (Phase 4) on Po Lam Road, Kowloon, and another is a public housing project (Phase 1) on Cheung She Wan West, New Territory; and the private housing project is Royal Peninsula adjacent to the KCR Kowloon Terminus, Kowloon. The construction sites study was conducted during the stage of superstructure works until finish works, from November 1999 to April 2000.

The typical public housing block in Hong Kong is a multi-floor reinforced concrete (RC) residential building with about 40 floors. The construction technologies of public housing block buildings are summarized in Table 4.2.

According to our site surveys of superstructure works of the residential projects, construction waste generated mainly includes wastage of cement, concrete rubbles, drywall scraps, wood scraps, rebar scraps, concrete block scraps, plastic conduit tailings, material packing and containers, nails, and other unused materials. For example, a site survey of public housing projects shows (refer to Table 4.3) that different construction processes can generate different construction waste, and it is similar in private residential project.

The reason why different construction wastes are generated from different construction processes can be divided into four sections, including construction technology, management, method, materials, and workers.

4.2.1 Construction technology

Both prefabrication technology and in situ technology of reinforced concrete are used in residential projects. The prefabrication technology generates almost no

Table 4.2 Construction technologies of public housing block in HK

Stage	*Technologies*
Site formation and clearance works	Demolition, site levelling
Foundation works	Precast RC pile, excavation, in situ RC foundation
Superstructure works	Precast RC external wall panel, in situ RC load-bearing wall, corridor and slab, semi-precast RC slab, precast concrete internal drywall, precast RC staircase, precast concrete block
Finish works	In situ external and internal plastering and coating, external wall and floor tiling
Other works	Batching plant, tyrewasher system, precast plant, transportation

Table 4.3 Construction waste generated from construction processes

Construction process	*Construction waste*								
	Concrete rubble	*Drywall scrap*	*Block scrap*	*Cement wastage*	*Wood scrap*	*Rebar tailing*	*Nail*	*Plastic conduit tailing*	*Material packing and container*
Fix wall rebar						✓		✓	
Place precast									✓
Place wall form					✓	✓*			
Concrete wall	✓			✓					✓
Strip wall form	✓								
Place precast									
Fix timber slab				✓	✓		✓		
Fix slab rebar						✓		✓	
Concrete slab	✓			✓					✓
Fix drywall		✓							
Bond block			✓						

Note
* When through-wall sleeve cannot be fixed easily, wall rebar will be cut.

construction waste because there is no need to use rebar, wood form, and in situ concrete, etc. on the site. On the other hand, in situ technology generates wastage of rebar, timber, and concrete, etc. during the process of construction, which is difficult to prevent on site.

4.2.2 Management method

In the site survey, it has been noticed that most construction wastes were generated due to the disorder of construction site layout. In some sites, materials and tools were placed everywhere, and as a result some unused materials and tools were messed up with the wastes and were eventually removed as wastes. Therefore, methods for managing and controlling wastes influence the amounts of wastes generated on site. For example, the introduction of waste storage containers (refer to Table 4.4) help to sort out various types of wastes. These sorted wastes are easy to recycle and re-use.

Obviously, these waste management methods can systematically sort out construction wastes on the sites; they cannot reduce construction wastes generated from every process. For example, the drywall board is a kind of solid slab, when workers fix pipelines, they cut the slab as they like and do not think about the amount of cuts and concrete fillings, and waste is thus generated. In the current management practice, the site waste manager's duty is only to collect the wastes and ensure the site is neat. In order to reduce the wastes, it is necessary to make innovations in the management of materials and equipments such as training to workers to reduce avoidable wastes, and due reward to workers for the good practices in cutting down wastages. One reason why the current management method cannot effectively reduce waste on construction sites is that it cannot effectively control the generation of construction waste due to the faults of construction techniques, building materials, workers, etc. From this point of view, innovative management methods are required to decrease any fault in waste reduction.

4.2.3 Materials

Two kinds of construction wastes originated from construction materials: materials packaging and materials wastage discarded on the construction site. Because construction packaging made of kraft paper and timber, and cartons are

Table 4.4 Current measures for construction waste management on site

Construction waste	*Management measure*
Rebar	Useless rebar collection skip
Concrete, Drywall, Block, Timber	Useless concrete transport pipe and collection skip
Water	On-site waste water treatment system
Other solid waste	On-site waste barrel

necessary for packing construction materials such as cement, wall tile, mosaic, and concrete nail, etc., the packaging unavoidably becomes part of the waste when materials are unpacked on site.

4.2.4 Workers

Workers take part in construction activities, and the survey shows that their attitude towards construction operations can make a big difference in terms of construction waste generation. Specifically, it is observed that if workers do not handle the materials with sufficient care then they will waste more materials, and vice versa. It has been observed that one of the main causes of material waste generation is incorrect or careless use of materials by workers on site. These kinds of wastes can be avoided or reduced if workers are motivated to be more conscious and responsible.

4.3 Avoidable material wastes caused by workers

Without careful control and rewarding systems, construction workers may become careless in handling construction materials. As a result, reusable reinforcement bars, discarded half-bags of cement, discarded nails and timber pieces are often thrown around the sites. Table 4.5 gives examples of avoidable wastes caused by workers in public housing projects in Hong Kong.

Table 4.5 indicates that skill, enthusiasm, and collectivism are the main factors affecting the amounts of wastes produced by workers. Among these three factors, workers' attitude towards their work, including their enthusiasm and collectivism, is regarded as the most important aspect in terms of waste generation, while their skill levels are relatively less important. In other words, if workers do not take

Table 4.5 Avoidable wastes caused by workers in public housing projects in HK

Construction process	*Avoidable wastes caused by workers*
Fix wall rebar	Extra processed rebar, arbitrarily cut rebar, abandoned rebar tailing, etc.
Place precast facade	Damaged facade board, broken scraps during erection
Place wall form	Arbitrarily cut and drilled plywood board, abandoned plywood board
Concrete wall	Left-over mixed concrete, excess concreting, etc.
Strip wall form	Damaged forms
Place precast slab	Damaged slab boards, broken scraps during erection
Fix timber slab	Arbitrarily cut and drilled plywood boards, abandoned plywood boards
Fix slab rebar	Extra processed rebar, arbitrarily cut rebar, abandoned rebar tailing, etc.
Concrete slab	Left-over mixed concrete, excessive concreting, etc.
Fix drywall	Arbitrarily cut drywall board, damaged drywall board, broken scraps, etc.
Bond block	Extra mortar, extra delivered blocks, cut and abandoned blocks, etc.

care of what they are doing then more materials will be wasted. So it is important to establish an on-site construction material management system to encourage construction workers to use materials carefully, and to enhance their enthusiasm and collectivism by rewarding them based on their good performances in saving materials through reducing operational mistakes, returning unused materials for re-use or recycle, etc.

It has been pointed out that because most residential buildings adopt standard designs prepared by the Housing Authority of the Hong Kong SAR government, such as the Harmony series, and are constructed by similar methods such as 4-day cycle and 6-day cycle, factors such as design coordination do not have major impacts on the generation of material wastes. How to enhance workers' enthusiasm and collectivism in minimizing construction wastes thus becomes more important in residential projects in Hong Kong.

4.4 Incentive reward program

It was observed in our site surveys that construction materials are taken from the storage areas on site without effective control, and placed with poor organization, especially in large projects or during urgent construction processes. The construction-material control system to be established aims to provide an effective tool for the project manager to manage on-site materials, and to motivate workers to reduce material waste to its minimum.

Research on the relationship between motivation and productivity in the construction industry has been conducted over the last 40 years (Olomolaiye *et al.* 1998). Productivity is dependent upon motivation, and motivation is in turn dependent on productivity (Warren 1989). A comparison of labour productivity for masonry activities from seven countries, including Australia, Canada, England, Finland, Scotland, Sweden, and the United States, reveals that there is little difference in productivity in the seven countries despite significant differences in labour practices, and the principal difference is management influence (Thomas *et al.* 1992). This viewpoint is replenished with a case study focusing on the impact of material management on productivity, which shows that ineffective material management could incur losses of productivity (Thomas *et al.* 1990). On the other hand, a series of comparative evaluations of labour productivity rates amongst French, German, and UK construction contractors indicate that German workers are likely to be highly motivated (because they are highly paid and regarded to be on a par with people doing intellectual and scientific work), and hence, more productive (Proverbs *et al.* 1998). All these research results reinforce that higher motivation brings higher productivity.

According to Maslow's motivation theory (Warren 1989), beyond their safety and health needs, workers require both emotional and financial rewards for exercising self-discipline in handling construction materials. There are many forms of rewards and punishments for workers' performance measure (Nelson 1994). Among these positive and negative rewarding (punishing) methods, some have been used on construction sites. For example, the use of special motivational programs and financial incentive programs (FIPs) have been reported (Laufer and Jenkins 1982; Liska and Snell 1993; Carberry 1996; Olomolaiye *et al.* 1998). The FIP is an important method for motivating workers, and it has been proved to be effective in improving quality and reducing project time and cost (Laufer and Jenkins 1982). Furthermore, the FIP has been widely accepted as a performance-dependent monetary reward system in the construction industry (Merchant 1997). So the IRP developed in this study is designed based on the principle of FIP, in order to meet the demand of on-site construction material management.

Fairness is an important consideration in designing the IRP; less fairness or unfairness would result in the failure of the IRP and may even have adverse effects on a construction project. Before the IRP is implemented, its fairness should be examined carefully. There are two aspects of fairness in the IRP: one is fairness to workers, another is its fairness to the firm. Fairness to the firm is easy to investigate. Because the IRP relates to the amount of construction materials consumed on site, if the overall amounts of construction wastes are reduced, then the firm will benefit. So the firm should share the benefits (saved money) with the contributors – workers.

The fairness of the IRP to workers is different. Workers are normally organized into gangs or groups according to their trades or types of work. Material is normally shared within the group. If an amount of material waste is detected, who should be punished, or, if there is a reduction of waste, who should be rewarded – the person who is responsible for shifting material from storage, or the leader of the group? Based on discussions with the project managers and workers involved in the projects we surveyed, we decided to adopt a group-based IRP. In the group-based IRP, members of the group will be rewarded or punished equally should there be any reduction and increase of material wastes. Group-based rewards provide a common goal for group members and encourage cooperation among members to achieve a higher performance, and it avoids the difficulty in determining an individual's contribution (Laufer and Jenkins 1982; Merchant 1997).

In the group-based IRP, each working group has a group leader who is responsible for collecting all the materials needed by his group from the store keeper. The store keeper records the amount of materials taken by each group. When a group finishes its work, the group leader is also responsible for arranging any unused materials to be returned back to the store keeper for updating the records.

Once a construction operation is completed, the project manager can measure the amount of material waste reduced or increased by comparing the actual amount of material used by the group with the estimated amount. The actual amount of material used is recorded by the store keeper, while the estimated amount of material is prepared by the contractor's quantity surveyors. The estimated amount includes a percentage which is considered as a normal amount of waste on site. The percentage is determined based on the contractor's experience from the levels of wastes in past projects.

For a particular type of material i, the performance of group j in terms of material wastage can be measured using Equation 4.1.

$$\Delta Q^i(j) = Q^i_{\text{estimated}}(j) - (Q^i_{\text{delivered}}(j) - Q^i_{\text{returned}}(j)) \tag{4.1}$$

where $\Delta Q^i(j)$ is the extra amount of material i saved (if the amount is a positive value) or wasted (if the amount is a negative value) by group j; $Q^i_{\text{delivered}}(j)$ denotes the total quantity of material i requested by group j; and $Q^i_{\text{estimated}}(j)$ denotes the estimated quantity that includes the statistic amount of normal wastage. The value of $Q^i_{\text{estimated}}(j)$ has to be carefully decided according to the circumstances of construction projects and previous experience (Schuette and Liska 1994; CIOB 1997). The $Q^i_{\text{returned}}(j)$ is the quantity of unused construction materials returned to the store by group j.

At the end of the project, the overall performance of group j can be measured by Equation 4.2.

$$C^i(j) = \sum_n \Delta Q^i(j) \times P_i \tag{4.2}$$

where $C^i(j)$ denotes the total amount of material i saved (if $C^i(j)$ is positive) or wasted (if $C^i(j)$ is negative) by group j; n is the total number of tasks in the project that need to use material i; and P_i is the unit price for material i.

The contracting company has to develop a policy to specify how the company shares the costs/benefits incurred from the reduction or increase of material wastes with workers. For example, the company may decide that workers should share 40% of the $C^i(j)$. In other words, the company will give back 40% of the $C^i(j)$ to workers as rewards. The rewards can be positive if the value of $C^i(j)$ is positive; and it can be negative (penalties) if the value of $C^i(j)$ is negative.

4.5 Implementation of IRP using bar-coding technology

4.5.1 Bar-code applications in construction

Since late 1980s, bar-code technology has been applied to many fields in construction as an automatic identification technology that streamlines identification and data collection on site. The application areas of bar-code technology in construction include quantity takeoff, field material control, warehouse inventory and maintenance, equipment/tool and consumable material issue, timekeeping and cost engineering, purchasing and accounting, scheduling, document control, office operations, and other information management in construction processes of projects (Stukhart and Pearce 1988; Stukhart and Pearce 1989; Stukhart and Cook 1989; Bernold 1990a,b; Stukhart and Cook 1990; Stukhart and Nomani 1992; McCullouch and Lueprasert 1994; Stukhart 1995; Bell and McCullouch 1998;

Chen and Li *et al.* 2000/2004). Some published studies regarding applications of bar-code technology in the construction industry are summarized in Table 4.6.

Although the bar-code technology has been used to control hazardous waste, including tracking information on hazardous material consumption and hazardous waste generation in the United States (Kemme 1998), no previous study has attempted to apply bar-code technology to minimize construction waste on sites before a crew IRP-based bar-code system was introduced (Li *et al.* 2003b). However, continued research of the crew IRP-based bar-code system conducted by the authors of this book shows that the proposed application is an efficient and

Table 4.6 Research and applications of bar-code technology in construction

Researcher	*Year*	*Project*	*Field*
Bell and Mc Cullouch	1988	Research	Potential applications
Stukhart *et al.*[a]	1988/1995	CII Research	Standardization
Lundberg and Beliveau	1989	Construction projects	Security management of M&E
Rasdorf and Herbert	1989/1990a,b	Construction projects	Workforce and inventory management
Blakey	1990	Construction projects	Facility management
Bernold	1990a,b	Testing	Construction environment
Brandon and Stadler	1991	Construction projects	Geotechnical data collection
Skibniewski and Wooldridge	1992	Construction projects	Robotic materials handling system
Baldwin *et al.*	1994	Precast concrete projects	Precast components management
McCullouch and Lueprasert	1994	Construction projects	Facility management
Stanley-Miller construction company	1996	Construction projects	Warehouse management
Echeverry *et al.*[b]	1996/1998	Construction projects	Personnel and materials management
Kemme	1998	Construction projects	Hazardous waste management
Wirt *et al.*	1999	Wastewater treatment plant	Equipment management
Li *et al.*	2003b	Construction projects	Waste minimization

Notes
[a] Stukhart and Pearce, 1988; Stukhart and Pearce 1989; Stukhart and Cook, 1989; Bernold 1990a,b; Stukhart and Cook 1990; Stukhart and Nomani 1992; McCullouch and Lueprasert 1994; Stukhart 1995; Bell and McCullouch 1998; Chen and Li *et al.* 2000/2004;
[b] Echeverry 1996; Echeverry and Beltran 1997; Echeverry *et al.* 1998.

cost-effective approach to integrating environmental management with project management in construction by implementing the crew-oriented IRP to minimize construction waste on sites.

4.5.2 Bar-coding system for IRP

As mentioned above, bar-code applications have been introduced to the construction industry since 1987 for material management, and plant and tool control (Bell and McCullouch 1988; Bernold 1990a,b; McCullouch and Lueprasert 1994; Stukhart 1994). The primary function of the bar-coding system is to provide instant and up-to-date information of quantities of materials exchanged between the store keeper and the group leaders/foremen. Specifically, implement IRP for reducing construction waste the bar-coding system can automatically

- track real-time data of new construction materials on the site;
- track real-time data of unused materials on the site;
- track real-time data of packing of materials and equipments;
- track real-time waste debris of materials on the site;
- record data of construction materials consumed in the project;
- monitor materials consumption of working groups;
- transfer real-time data to project management system;
- transfer real-time data of materials to head office via the Net.

The architecture of the bar-code system used in this implementation is illustrated in Figures 4.1 and 4.2. From these figures, it can be seen that when the group leader goes to the store to withdraw new materials or return surplus materials, the store keeper scans the bar-code labels for the materials as well as the bar-coding label/ID card of the group, so that the amounts of materials taken or returned by the group are registered in the database. Based on the amounts of materials initially ordered according to the estimated requirements, and the materials used by working groups, the computer system can calculate the value of $C^i(j)$ for each group j. Bar-codes are given to each item (if it is big, e.g. door, window, etc.) or each pack (if the items are small, e.g. pack of nails, bolts and nuts).

4.5.3 Material identification

For the materials, the bar-coding labels are designed to represent a material and its model, etc. For example, the code *0002-525-1-XYZ* represents “Cement – Portland, Ordinary 525# – 1 standard bag – XYZ Trademark”, the code *0201-003-1-Local* represents “Aggregates – 3 mm particle diameter – 1 cubic meter – Local provenance”, as shown in Figure 4.3. The “Class No.” in Figure 4.3 is used to represent names of different materials, and the total number of the “Class No.” is set as 2,000. The bar-code adopted for materials is Code 128 symbology (Stukhart 1995), and the codes are designed to represent Material, Model and

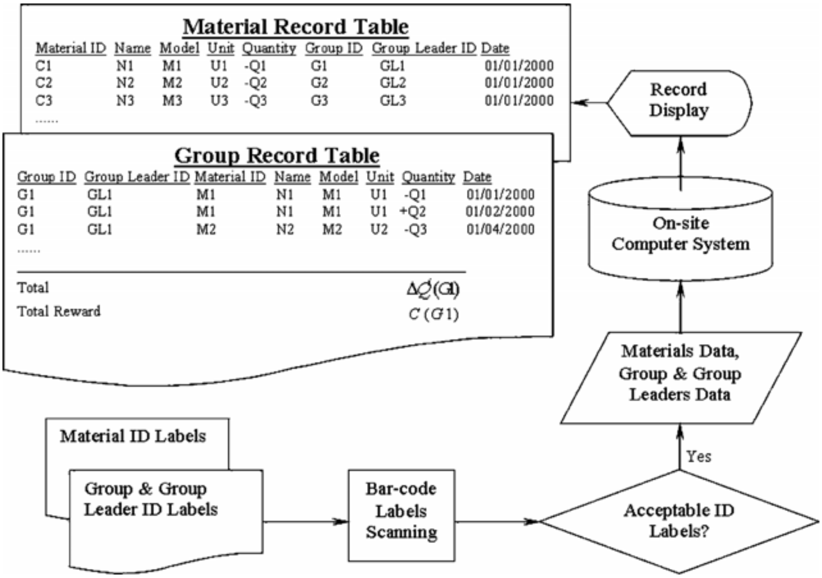


Figure 4.1 Data flow diagram of the bar-code system for group-based IRP.

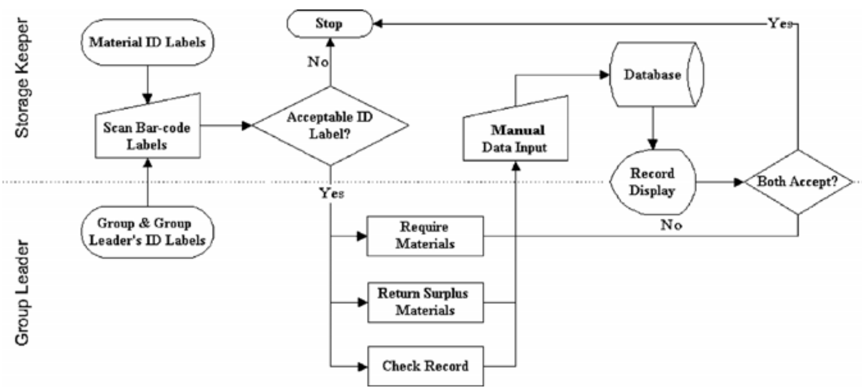


Figure 4.2 Data flowchart of the bar-coding system for group-based IRP.

Quantity. For example, the code *0001-19-1* represents "plywood formwork – 19 mm thick – 1 square meters", as shown in Figure 4.3.

Because bar-code labels can be easily damaged during transportation and are cumbersome to scan if they are adhered onto the items/packs, we prepared a handbook of bar-code labels for all the construction materials used on site. This

ABC CONSTRUCTION CO., LTD.
Hung Hom, Kowloon, Hong Kong
Construction Material Management System
Bar-Code Lable
Material Description
Name: Plywood formwork
Class No.: 0001
Model: 19 mm thick
Quantity Unit: 1 sq m
Material ID No.: 0001-19-1
0001-19-1

ABC CONSTRUCTION CO., LTD.
Hung Hom, Kowloon, Hong Kong
Construction Material Management System
Bar-Code Lable
Material Description
Name: Cement
Class No.: 0002
Model: Portland, ordinary 525#
Quantity Unit: 1 bag
Material ID No.: 0002-525-1
0002-525-1

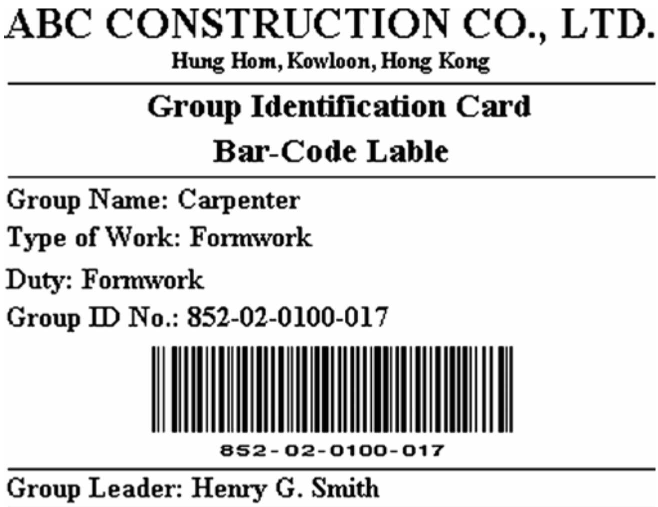
Figure 4.3 Sample bar-coding labels for construction materials.

handbook contains all the bar-codes and is maintained and used by the material store keeper.

4.5.4 Working-group identification

For each working group, an identification card is issued to the group leader, who is responsible for collecting and returning construction materials. Figure 4.4 gives a sample identification card for a working group.

The bar-code of the group represents the group and its leader. For example, ID number *852-02-0100-017* represents “Carpenter group 852 and its leader’s staff ID number is 02-0100-017”, as shown in Figure 4.4. By scanning the bar-codes for the materials and the group, the computer system keeps records of materials



ABC CONSTRUCTION CO., LTD.
Hung Hom, Kowloon, Hong Kong

Group Identification Card
Bar-Code Lable

Group Name: Carpenter
Type of Work: Formwork
Duty: Formwork
Group ID No.: 852-02-0100-017

852-02-0100-017

Group Leader: Henry G. Smith

Figure 4.4 Bar-coding label/ID card for a carpenter group.

used or returned by the group. These records are then used to calculate the reduction in or increase of material wastes generated by the group.

4.5.5 Hardware system

The hardware system of the bar-coding application consists of the bar-code scanner and the computer. A basic bar-code scanner consists of a scanner, a decoder, and a cable that interfaces between the decoder and the computer or terminal. Although there are four basic styles of bar-code scanners – light pen (usually called wand), linear CCD (charge-coupled device), laser, and video (CCD array) – the most versatile bar-code scanners are laser scanners, and many scanners have the decoder logic incorporated into a chip within the scanner, eliminating the need for a separate piece of hardware (PIPS 2001). The scanner we selected is PSC QuickScan 5385 scanner with keyboard wedge type of decoder integrated, which allows bar-code scanning to be added to almost any application without modification to the application software (PIPS 2001). Figure 4.5 illustrates the bar-coding hardware system.

4.5.6 Software system

The software system for a bar-code technology includes two essential software: bar-code–labelling software and bar-code–tracking software. Bar-code technology providers such as Loftware LLM-WIN32, BAR-ONE, and Bar-Tender, provide fast and easy-to-use bar-code–labelling software for designing

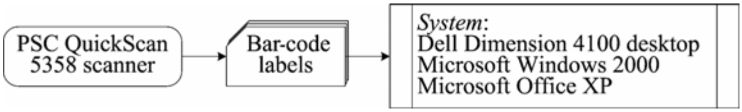


Figure 4.5 Components of the bar-coding hardware system.

and printing quality labels. Bar-code–tracking software, such as IntelliTrack and Inventory Manager, can be used to read and track the bar-codes.

The bar-code adopted here is Code 128 symbology (Stukhart 1995). Software named "LLW-Win32 Design" (Version 5.x) from Loftware label printing systems is used to design the identification labels, and all bar-coding labels are printed out through a HP LaserJet printer. Identification of bar-coding labels is done using a handbook of bar-coding labels for all kinds of construction materials used on different sites, as discussed earlier.

4.5.7 Experimental results

A public housing project in Hong Kong was selected to experiment the group-based IRP. The project involved constructing two identical 34-storey residential blocks using a 6-day cycle. The 6-day cycle included nine major activities undertaken by nine working groups. The two blocks were constructed simultaneously by two teams of workers, each team having nine working groups with equal numbers of workers to carry out the 6-day-cycle construction method. We labelled the two teams as Team A and Team B. For the purpose of comparison, Team A did not adopt the group-based IRP during their operations, while Team B implemented the IRP with our advice and support.

The experiment has been conducted over three months. Results from Team's A and B during the three months are listed in Tables 4.7 and 4.8. The first column of the tables is the list of major materials used in the 6-day cycle. The second column is the unit of the materials; the third column contains the group names and their tasks. Columns 4–6 list estimated quantities of materials, quantities of materials delivered to groups, and quantities returned by groups. Column 8 lists the prices of materials, while columns 7–9 list results of calculations based on Equations 1 and 2. From the experimental results, it can be observed that throughout the three months, Team A consistently wasted more construction materials than Team B because workers in Team A did not see the benefits of reducing wastes. Therefore, by the end of three months, Team A had wasted additional amounts of construction materials valued at US$95,890.73 (HK$747,947.71). In contrast, Team B had made a substantial saving of US$90,428.83 (HK$705,344.85), indicating that the group-based IRP had effectively motivated workers in Team B in reducing avoidable wastes. The difference between the two projects is US$186,319.56 (HK$1,453,292.5). The cost of the bar-code system is

Table 4.7 Experimental results without group-based IRP (Team A)

Materials	*Unit*	*Group*		$Q^i_{estimated}(j)$	$Q^i_{delivered}(j)$	$Q^i_{returned}(j)$	$\Delta Q^i(j)$	P_i	$C(j)$
		Name	*Duty*						
Rebar	ton	Steel bender	Fix wall rebar	1, 760.00	1, 795.20	0.00	−35.20	2, 271.31	−79, 950.11
			Fix slab rebar	1, 408.00	1, 425.60	0.00	−17.60	2, 271.31	−39, 975.06
Precast facade	set	Rigger	Place precast façade	1, 760.00	1, 760.00	0.00	0.00	3, 000.00	0.00
Precast slab	set		Place precast slab	9, 856.00	9, 856.00	0.00	0.00	1, 500.00	0.00
Cement	ton	Concreter	Concrete wall	31, 680.00	31, 715.20	0.00	−35.20	640.80	−22, 556.16
			Concrete slab	10, 560.00	10, 630.40	0.00	−70.40	640.80	−45, 112.32
		Plasterer	Fit up wall, ceiling and floor	15, 400.00	15, 554.00	0.00	−154.00	640.80	−98, 683.20
Sand	cubic meter	Concreter	Concrete wall	26, 928.00	27, 280.00	0.00	−352.00	57.04	−20, 078.08
			Concrete slab	10, 560.00	11, 264.00	0.00	−704.00	57.04	−40, 156.16
		Plasterer	Fit up wall, ceiling and floor	24, 024.00	24, 670.80	0.00	−646.80	57.04	−36, 893.47
Cobblestone	cubic meter	Concreter	Concrete wall	26, 752.00	27, 456.00	0.00	−704.00	58.30	−41, 043.20
			Concrete slab	10, 560.00	11, 264.00	0.00	−704.00	58.30	−41, 043.20
Hydrated lime	ton	Plasterer	Fit up wall, ceiling and floor	9, 394.00	9, 424.80	0.00	−30.80	464.00	−14, 291.20
Plywood formwork	square meter	Carpenter	Fix timber slab form	26, 400.00	27, 280.00	0.00	−880.00	57.20	−50, 336.00
Nail	bag		Fix timber slab form	1, 760.00	2, 640.00	0.00	−880.00	50.10	−44, 088.00
Drywall board	square meter	Rigger	Install wall board	9, 460.00	9, 900.00	0.00	−440.00	164.00	−72, 160.00
Block	10K blocks	Bricklayer	Bond masonry wall	2.20	2.75	0.00	−0.55	7, 296.12	−4, 012.87
Embedded plastic conduit	meter	Electrician	Conceal conduit installation	18, 480.00	22, 000.00	0.00	−3, 520.00	1.05	−3, 696.00
Glass	square meter	Glazier	Install window glass	8, 078.40	8, 448.00	0.00	−369.60	27.80	−10, 274.88
Paint	square meter	Painter	Fit up minor works	468.60	484.00	0.00	−15.40	25.00	−385.00
Wall tail	square meter	Plasterer	Fit up wall	22, 704.00	23, 760.00	0.00	−1, 056.00	34.00	−35, 904.00
Mosaic	square meter		Fit up wall and floor	10, 824.00	11, 352.00	0.00	−528.00	89.60	−47, 308.80
			Total (HK$)						−747, 947.71

Table 4.8 Experimental results with group-based IRP (Team B)

Materials	*Unit*	*Group*		$Q^i_{estimated}(j)$	$Q^i_{delivered}(j)$	$Q^i_{returned}(j)$	$\Delta Q^i(j)$	P_i	$C(j)$
		Name	*Duty*						
Rebar	ton	Steel bender	Fix wall rebar	1, 760.00	1, 724.80	17.60	52.80	2, 271.31	119, 925.17
			Fix slab rebar	1, 408.00	1, 372.80	17.60	52.80	2, 271.31	119, 925.17
Precast facade	set	Rigger	Place precast façade	1, 760.00	1, 760.00	0.00	0.00	3, 000.00	0.00
Precast slab	set		Place precast slab	9, 856.00	9, 856.00	0.00	0.00	1, 500.00	0.00
Cement	ton	Concretor	Concrete wall	31, 680.00	31, 609.60	17.60	88.00	640.80	56, 390.40
			Concrete slab	10, 560.00	10, 454.40	17.60	123.20	640.80	78, 946.56
		Plasterer	Fit up wall, ceiling and floor	15, 400.00	15, 276.80	15.40	138.60	640.80	88, 814.88
Sand	cubic meter	Concretor	Concrete wall	26, 928.00	26, 576.00	105.60	457.60	57.04	26, 101.50
			Concrete slab	10, 560.00	10, 384.00	211.20	387.20	57.04	22, 085.89
		Plasterer	Fit up wall, ceiling and floor	24, 024.00	23, 870.00	123.20	277.20	57.04	15, 811.49
Cobblestone	cubic meter	Concretor	Concrete wall	26, 752.00	26, 576.00	246.40	422.40	58.30	24, 625.92
			Concrete slab	10, 560.00	10, 384.00	211.20	387.20	58.30	22, 573.76
Hydrated lime	ton	Plasterer	Fit up wall, ceiling and floor	9, 394.00	9, 332.40	3.08	64.68	464.00	30, 011.52
Plywood formwork	square meter	Carpenter	Fix timber slab form	26, 400.00	26, 048.00	140.80	492.80	57.20	28, 188.16
Nail	bag		Fix timber slab form	1, 760.00	1, 584.00	88.00	264.00	50.10	13, 226.40
Drywall board	square meter	Rigger	Install wall board	9, 460.00	9, 350.00	0.00	110.00	164.00	18, 040.00
Block	10K blocks	Bricklayer	Bond masonry wall	2.20	2.15	0.22	0.28	7, 296.12	2, 006.43
Embeddedplastic conduit	meter	Electrician	Conceal conduit installation	18, 480.00	18, 004.80	176.00	651.20	1.05	683.76
Glass	square meter	Glazier	Install window glass	8, 078.40	7, 867.20	26.40	237.60	27.80	6, 605.28
Paint	square meter	Painter	Fit up minor works	468.60	462.00	2.20	8.80	25.00	220.00
Wall tail	square meter	Plasterer	Fit up wall	22, 704.00	22, 545.60	132.00	290.40	34.00	9, 873.60
Mosaic	square meter		Fit up wall and floor	10, 824.00	10, 718.40	132.00	237.60	89.60	21, 288.96
			Total (HK$)						*705,344.85*

about HK$150,000. Thus, Team B has about HK$550,000 savings. These results convinced us that group-based IRP is effective in reducing construction wastes.

4.5.8 Crew IRP-based bar-code system

The crew IRP-based bar-code system comprises a crew-oriented IRP with a bar-code system (Li *et al.* 2003b). Previous research showed that the skill and attitude of workers are the main factors affecting the amounts of waste produced by workers (Pilcher 1992); between these two factors, their attitude towards work, including their enthusiasm and collectivism, is the most important in terms of waste generation. In addition, site surveys (Poon *et al.* 1996; Poon and Ng 1999) also indicated that workers' attitude towards construction operations and materials can make a significant difference to the amount of construction waste generated, and they may become careless in handling construction materials if there were lack of careful control and rewarding systems. As a result, reusable materials such as reinforcement bars, half-bags of cement, nails and timber pieces, etc. are often thrown away around the sites. The authors introduced the crew-based IRP thereafter in order to meet the demand of on-site construction material management. It is important to establish an on-site construction material management system to encourage workers to use materials carefully and efficiently, and to enhance their enthusiasm and collectivism by rewarding them according to their good performances in saving materials through reducing operational mistakes, returning unused materials for re-use or recycle, etc. (Li *et al.* 2003b). The crew IRP was conducted for on-site material management based on motivation theory by Maslow *et al.* (1998) and its development to CM such as the uses of special motivational programmes, and financial incentive programmes (Laufer and Jenkins 1982; Carberry 1996; Merchant 1997; Olomolaiye *et al.* 1998; Li *et al.* 2003b). It is expected that the crew IRP can help on-site CM to reduce any avoidable material waste caused by workers who may misuse materials on site.

As it is a quantitative approach to measuring the amount of material waste possibly generated in each construction process and each construction project, the computation of the crew IRP is done by using Equation 4.3.

$$C_i(j) = \sum_n \Delta Q_i(j) \times P_i = \sum_n (Q_i(j)_{\text{es}} - [Q_i(j)_{\text{de}} - Q_i(j)_{\text{re}}]) \times P_i \qquad (4.3)$$

where $C_i(j)$ is the total amount of material i saved (if it is positive) or wasted (if it is negative) by crew j; $\Delta Q_i(j)$ is the extra amount of material i saved (a positive value) or wasted (a negative value) by crew j; P_i is the unit price for material i; $Q_i(j)_{\text{es}}$ is the estimated quantity that includes the statistic amount of normal wastage; $Q_i(j)_{\text{de}}$ is the total quantity of material i requested by crew j;

$Q_i(j)_{re}$ is the quantity of unused construction materials returned to the storage by crew j; i is number of any construction material that may be requested by a crew; j is number of any construction crew whose operations may potentially generate waste; and n is the total number of tasks in the project that need to use material i.

According to Equation 4.1, for a particular type of material i, the performance of crew j in terms of material wastage can be measured by $\Delta Q_i(j)$, and at the end of the project, the overall performance of crew j can be rewarded in agreement with $C_i(j)$. This means that the IRP is implemented according to the amount of materials saved or wasted by a crew i.e. if a crew save materials ($\Delta Q_i(j) > 0$); the project manager will then award the crew a prize based on the amount of $C_i(j)$. In Equation 4.1, the value of $Q_i(j)_{es}$ has to be carefully decided according to the circumstances of construction projects and previous experience (Schuette and Liska 1994; CIOB 1997). On account of the requirement to increase the precision in reward through computation, a knowledge-driven system was introduced to re-use CM knowledge to more accurately define the value of $Q_i(j)_{es}$ (Chen and Li *et al.* 2005).

On the other hand, as construction waste is often generated due to misuse of materials by workers, the implementation of the crew IRP requires an efficient and cost-effective on-site material management system, and the bar-code system was thus adopted to implement the crew IRP (Li *et al.* 2003b). Figure 4.6 illustrates the architecture of the crew IRP-based bar-code system, which can be utilized on site in each construction project as mentioned with Site X in the figure.

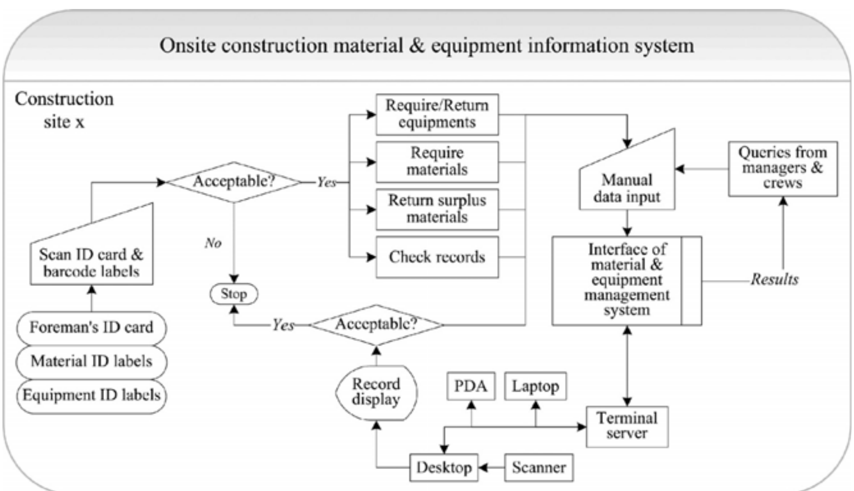


Figure 4.6 A conceptual model for the crew IRP-based bar-code system.

The conceptual model described in Figure 4.7 comprises three sections: data capture mechanism, data process mechanism, and hardware system. Regarding the on-site M&E management, the data capture mechanism allows store keepers to scan bar-code labels of each M&E on site whilst facilitating crews and managers to input requests or queries related to M&E information. Meanwhile, the data process mechanism records the information of M&E and runs the IRP computation so that crews and managers can collect information for further decision-making on waste reduction. For example, bar-codes have been given to each M&E item and each pack; when a foreman goes to the store to request new materials or to return surplus materials, the store keeper scans bar-code labels corresponding to the materials as well as the ID number of the foreman, so as to collect information, such as the amount of materials taken or returned by the crew, for the M&E database. After the data collection, computations of IRP are done based on the amounts of materials initially requested by each crew but limited by the estimated quantities of each material, and the materials finally used by crews, and a software can calculate the value of $C_i(j)$ for each crew j. The value of $C_i(j)$ can thereafter be used to implement the IRP.

The hardware of the crew IRP-based system includes an on-site terminal computer server system, and immobile/mobile bar-code laser scanners. Table 4.9 gives an example of the hardware and software components of a crew IRP-based system application.

In this application example, bar-code representation adopted is the Code 128 symbology (Stukhart 1995), using Loftware® Label Manager to design the identification labels, and all bar-coding labels are printed out through a HP LaserJet printer. For each material and equipment, one bar-coding label is designed to represent one corresponding material or equipment and its model, etc.; for example, the code *0002-525-1-X* represents “Cement – Portland, Ordinary 525# – 1 standard bag – Trademark X”, and the code *0201-003-1-Y* represents “Aggregates – 3 mm particle diameter – 1 cubic meter – Provenance Y” (Li *et al.* 2003b). One bar-coding label is designed to represent one crew; for example, coding number *586-01-0208-010* represents “Concretor crew 586 and its leader’s staff ID number is 01-0208-010”. By scanning the bar-codes for materials and crews,

Table 4.9 An example of crew IPP-based system application

Hardware
Dell® Dimension® 4100 desktop
PSC QuickScan® 5385 scanner with keyboard wedge type of decoder
Handbook of bar-code labels for construction M&E (internal)
Software
Microsoft® Windows® NT/XP
Microsoft® Office® XP
Loftware® Label Manager

the computer system keeps record of materials used or returned by the crew. All these records are further used to calculate the possible wastes from each crew. Experimental results indicated that there is about 10% material saving by implementing the crew IRP-based bar-code system (Li *et al.* 2003b).

4.6 IRP and quality-time assurance

As the IRP focuses on waste reduction on site, the construction process might be jerrybuilt when a worker group wants to excessively save materials. It is important to integrate the IRP with quality and time management during the whole construction project. In the Hong Kong construction industry, residential buildings are built based on standard designs; it is convenient for the quantity surveyors to accurately measure the exact amounts of materials consumed in each activity and process. Working groups and the group foremen will be seriously questioned if the groups reduced material consumption in certain activities or processes such that the actual amounts of used materials were near or below the exact amounts measured by the quantity surveyors. In addition, rigorous quality assessment has to be conducted to ensure that the quality level is maintained, and working groups who can reach high quality requirement will also be awarded besides the reward from the IRP. On the other hand, the IRP could affect the duration little in each construction process if we apply information technology, e.g. bar-coding technology, in its implementation, instead of manual recording and calculation.

4.7 Integration with GIS and GPS

4.7.1 Potentials of the crew IRP-based bar-code system

Generally, urban development directly leads to the increase of construction and demolition waste. Since 1970s, governments, practitioners, and academics have been advancing gradually in pursuance of efficient and cost-effective environmental management to reduce construction waste worldwide (Chen and Li *et al.* 2000/2005); however, the total amount of construction waste is still out of control due to rapid urban development and lack of effective tools for CM. The statistic chart presented in Figure 4.7 reveals a remarkably bullish tendency of C&D waste generation in Hong Kong in 1986–2003 while several thousand tons of C&D waste was disposed of at landfills everyday on average (HKEPD 1998a,b,c/2004a,b). With worldwide perspectives to the construction industry, the issue of minimizing construction waste is being dealt with through process reengineering, technique innovation, and information technology by environment-concious construction sectors. For example, Fishbein (1998) and Coventry *et al.* (1999) established a set of construction-waste prevention strategies focusing on the effective coordination of materials management, including efficient purchase and ordering of materials; just-in-time delivery; careful storage and the use of materials to minimize loss, maximize re-use, prevention of undoing and redoing; reduction of packaging

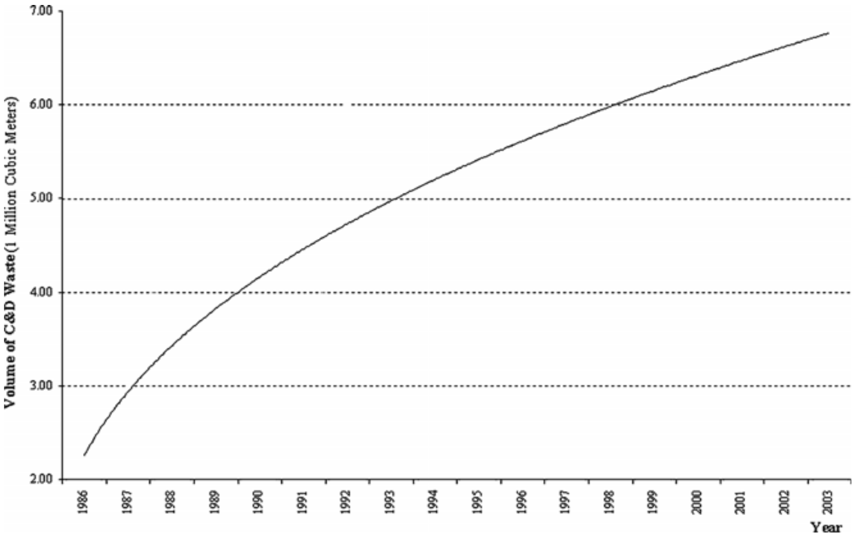


Figure 4.7 The amount of C&D waste: a case in Hong Kong (1986/2003) (Data source: EPD, HK).

waste, etc. Previous studies on the construction-waste prevention strategies indicated that it is an extra expense for construction sectors to adopt new equipment and to utilize automation technologies in their projects (Ho 1997) and most (about 68–85%) construction sectors would adopt these new technologies only when it is requested by designers, specifications, or clients (Poon *et al.* 1996; Poon and Ng 1999), as a result, the cost-effective applications of information technology (IT) such as Web-based waste information exchange system (Chen and Li *et al.* 2003) can thus promote the deployment of the construction-waste prevention strategies.

Regarding IT applications in the area of construction-waste management, a crew-based IRP (Chen and Li *et al.* 2002a) with a bar-code system for on-site construction material management has been introduced to reduce any avoidable wastes by rewarding workers according to the amounts and values of materials they saved from their operations with the prerequisite of quality assurance. Compared with other IT applications for construction-waste management such as Web-based information exchange system about waste (Chen and Li *et al.* 2003), the IRP-based bar-code system can provide instant and up-to-date information about the quantities of materials requested or returned by a crew to a store keeper on site. Specifically, the bar-code system can automatically track real-time data of new materials, material residuals, material/equipment packing, and waste debris on the site.

However, there are two potentials of the on-site bar-code system. First, construction supervisors can comparably monitor the consumption of materials and equipment (M&E) in any similar ongoing construction processes and projects by using the recorded historical data of M&E utilized in any previous projects.

Second, construction managers and headquarters can re-use real-time information of M&E captured from each construction site in classified project management systems, including on-site construction M&E information system and central construction M&E information system. These potentials have left a research and development space for a more efficient CM information system to facilitate M&E management throughout the headquarters and each project on the platform of a wide area network (WAN). Considering this, the objective of this section is to present an integrated M&E management system using the IRP-based bar-code technology, the global positioning system (GPS) technology, the geographical information system (GIS) technology, and the WAN technology to facilitate M&E management, to control and reduce construction wastes, and to increase efficiency in project-oriented CM.

The methodology of the research comprises a combination of research methods including the development of an integrated physical model for M&E management in the enterprise-wide environment of construction sectors based on an extended literature review regarding the application of bar-code, GPS, GIS and WAN technologies in construction, and the adoption of the proposed model in a case study. Methods for achieving individual objectives are described below.

As mentioned above, potentials of former crew IRP-based bar-code system have left an opportunity to upgrade it from project-based M&E information system to enterprise-wide M&E management system by integrating GPS technology and GIS technology on the WAN, which is a geographically dispersed telecommunications network.

4.7.2 GPS/GIS applications in construction

The integrated utilization of GPS and GIS technologies is being adopted in more and more civilian areas to facilitate decision-making based on real-time remote-sensing spatial information. GIS is a computer-based system to collect, store, integrate, manipulate, analyse, and display data in a spatially referenced environment, which assists in analysing data visually and seeing patterns, trends, and relationships that might not be visible in tabular or written form (U.S.EPA 2004a,c). The application areas of GIS technology for environmental management include site remediation, natural resources management, waste management, groundwater modelling, environmental impact assessment, policy assessment compliance permit tracking, and vegetation mapping, etc. (U.S.EPA 2004a,c). On the other hand, GPS is a satellite-based navigation system made up of a network of approximately 24 satellites, which were placed into orbit by the U.S. Department of Defense in the 1970s and circle the earth twice a day in a very precise orbit and transmit information to earth, where GPS receivers receive this information and use triangulation to calculate the user's exact location (U.S.EPA 2004a,b). The application areas of GPS technology for civilian utilization include public safety, emergency location, automobile navigation, vehicle tracking, airport surveillance, control surveys, radial surveys, site acquisition and surveying, digital network timing and synchronization, precision farming, farm vehicle automation, and field environmental decision support, etc. (Bossler 2001; Kennedy 2002; U.S.EPA 2004a,b). In addition to the separated use of GPS technology or GIS technology in the mentioned areas, the integrated utilization of GPS and GIS technologies for civilian purposes also has increased since the 1990s (U.S.EPA 2004a,b,c; Hampton 2004).

In the fields of construction, both GPS technology and GIS technology, and their integrated technology have been introduced synchronously to many areas such as transportation management, facility delivery, urban planning, jobsite safety monitoring, site layout and development, and business analysis, etc. (Li *et al.* 2003a; Hampton 2004). Some published studies and applications of GPS and GIS technologies in the construction industry are summarized in Table 4.10. According to literature summarized in Table 4.10, the research and development of GPS/GIS applications in the construction industry was initiated in the early 1990s and there is still so much potential in the field of GPS/GIS applications

Table 4.10 Research and applications of GPS/GIS technologies in construction

Researcher	*Year*	*System*	*Project*	*Field*
Selwood and Whiteside	1992	GIS	Civil engineering	Construction
Metcalf and Urban	1992	GIS	Highway corridor study	Highway construction
Bakken and Avey	1992	GIS	Water supply systems	Design and construction
Adams *et al.*	1992	GIS	Facility delivery	Urban planning
Williams	1992	GIS	Civil engineering	Construction
Jeljeli *et al.*	1993	GIS	Research	Contractor prequalification
Hammad *et al.*	1993	GIS	Bridge planning	Bridge construction
Launen	1993	GPS	Freeway monitoring	Transportation management
Parker and Stader	1995	GIS	Highway construction	Erosion predictions and control
Varghese and O'Connor	1995	GIS	Routing vehicles on sites	Construction planning
Issa	1995	GPS	Construction	Quality and productivity control
Robinson *et al.*	1995	GPS	Tunnel construction	Construction surveys
Nasland and Johnson	1996	GPS	Construction staking	Construction surveys
Cheng and O'Connor	1996	GIS	Site preparation	Construction planning
Udo-Inyang and Uzoije	1997	GIS	Highway construction	Inspection
Naresh and Jahren	1997	GPS	Vehicle tracking	Fleet management
Adams *et al.*	2000	GIS	Freeway monitoring	Oversize/weight permits
Wiegele	2000	GPS+GIS	Research	Pipeline construction
Cheng and Yang	2001	GIS	Site layout planning	Construction planning
Bernold	2002	GPS	Research	Construction engineering
Sacks *et al.*	2003	GPS	Labour monitoring	Workforce management
Li *et al.*	2003a	GIS	E-Commerce	Material procurement
Sukut	2003	GPS	Heavy equipment control	Fleet management
McFall	2004	GIS	Sewer revision	Pipeline construction

for construction sectors, comparing with the deployment of information systems in nearly all areas of construction engineering and management. In addition, most previous research and development focused on a single application of GPS technology or GIS technology, and the benefits of integrated GPS/GIS technology, which can bring highly efficient and cost-effective results to construction sectors, are still under excavation.

Although the integrated GPS/GIS technology has been used to provide decision-makers with the internal capability for rapid and effective contaminated site characterization (U.S.EPA 2004a,b,c), which is a typical utilization of the integrated technology in the area of environmental management to monitor and control adverse environmental impacts such as hazardous waste and noise, etc., there is no research initiative to apply the integrated technology to minimize adverse environmental impacts in construction such as construction waste and construction noise on sites. Since the integrated technology has been demonstrated to bring benefits in pipeline construction (Wiegele 2000), and either GPS technology or GIS technology can bring high efficiency and cost-effectiveness to construction sectors according to previous research and development (refer to Table 4.10), the authors further combine the crew IRP-based bar-code system with the integrated GPS/GIS technology to facilitate an enterprise-wide M&E management for the purpose of waste reduction. The proposed application will provide a highly efficient and cost-effective platform to assist the enterprise resource planning (ERP) implementation in the construction sector.

4.7.3 Integrated M&E management system

4.7.3.1 Enterprise-wide crew IRP-based bar-code system

The enterprise-wide crew IRP-based bar-code system is a development of project-wide crew IRP-based bar-code system, which is presented in Figure 4.7. The aim of this development is to enhance the efficiency utilization of M&E information throughout the headquarters of a construction sector and each construction site belonging to it, from which the headquarters and site managers are able to get real-time information of M&E within the enterprise so as to make any further decisions depending on the information, such as the implementation of crew IRP in each project and the deployment of M&E among all projects. In addition, the enterprise-wide crew IRP-based bar-code system is an effective addition to a general-purpose construction project management system or an ERP system for construction sectors by means of automatic M&E data collection and data input through a terminal computer server on each construction site to a central computer server in the headquarters. Since Figure 4.7 has given an on-site section of the enterprise-wide crew IRP-based bar-code system, the central section of the proposed system is presented in Figure 4.8. Considering the possibility of M&E data input at the headquarters, the component of crew IRP-based bar-code system is combined to the central construction project management system, and

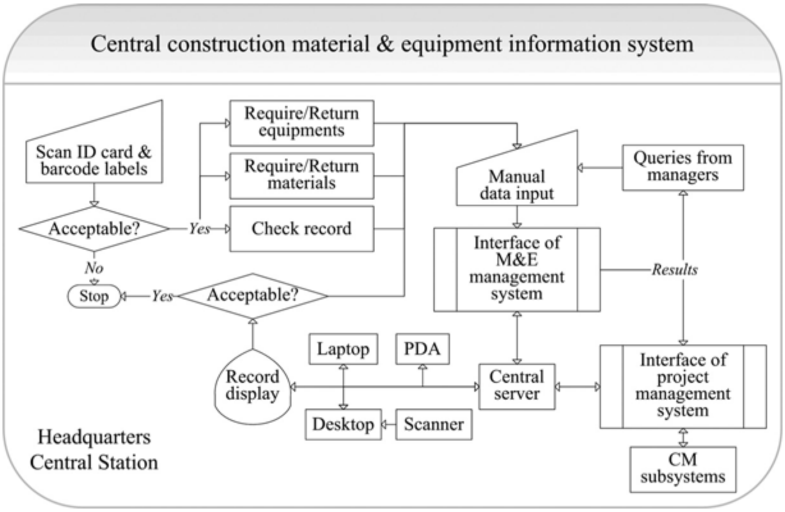


Figure 4.8 A conceptual model for the enterprise-wide crew IRP-based bar-code system.

this system structure may facilitate central control without any obstacles such as authorization and firewall to go into any on-site M&E subsystems.

The data transfer among on-site M&E systems, central M&E system, and central construction project management system requires physical support from WAN. There are two main types of data transfer:

1 Data from construction sites regarding
   - storage condition of M&E in each construction site,
   - demand of M&E from each individual construction site,
   - report of crew IRP from each construction site, and
   - query and pivot of M&E to other construction sites and the headquarters; and
2 Data from headquarters, regarding
   - query and pivot of M&E storage condition on each construction site,
   - query and pivot of M&E demand from each construction site, and
   - demands of M&E deployments from each construction site.

All this data transfer can be realized within a typical management information system, and the real-time communication between the headquarters and each construction site can be achieved based on the WAN. However, with the requirements of dynamic construction project management, the function and structure of traditional management information systems cannot provide satisfactory services regarding some real-time queries. For example, if managers from the headquarters want to know something about a kind of material, they may have questions about the present location of the material and its arrival time to a specific construction site (refer to Tables 4.11 and 4.12); but the limitation in information synchronization or real-time information capture in the traditional management information system necessitates an answer to these queries.

As a result, there is a requirement of plant information synchronization capacity for the traditional M&E management information system, and this capacity can make it easy to capture synchronous information from remote locations outside a construction site and the headquarters.

4.7.3.2 GPS/GIS integrated M&E management system

The integrated GPS/GIS technology adds new features such as construction vehicles tracking to the traditional M&E management information system for the propose of transferring real-time information about the location of any construction M&E that are being carried to a construction site from any locations outside the site. The integrated GPS/GIS technology helps to improve efficiency and increase profits by providing real-time vehicle locations and status reports, navigation assistance, drive speed and heading information, route history collection, etc. (Trimble 2004). Figure 4.9 illustrates the simple architecture of integrated GPS/GIS technology for the proposed M&E management system to reduce construction waste and to improve construction efficiency.

Regarding the cargo transportation of construction M&E, intercity freight transportation is dealt with in the proposed prototype (refer to Figure 4.9), including waterway transportation, air transportation, and overland transportation such as transportations by railroad and highway. Cargoes are fitted with GPS, which can transmit its positional data together with information about other attributes to the central station at the headquarters and distributed terminals on construction sites via the WAN. The central station at the headquarters is a monitoring station, where the accurate position of each construction cargo is displayed on a GIS map, and the information of each cargo can be queried. By using GIS analysis technology, the central station can get information about the current location of the cargo and estimate the time when the cargo can probably arrive at each predetermined construction site, i.e. its destination. Moreover, the central station also can send commands to drivers via personal digital assistants (PDAs) regarding cargo transportation and dispatch such as when they should start or which route they should pass through. This is very helpful for construction especially in a construction site where the space for material storage is limited; in theory, it is possible for zero storage on sites if the arrangement is precise and appropriate.

The deployment of the GPS/GIS integrated construction M&E management system requires physical support from computer hardware and software systems. The software requirements include computer operating system, GPS software, GIS software, and crew IRP-based M&E management system, etc. For example, a demonstration is developed in the Windows series of operating systems from Microsoft, including Microsoft Windows NT/2000/XP/CE and

Table 4.11 Real-time M&E information for supervisory control

Material ID	*Material name*	*Model*	*Unit*	*Quantity*	*Supplier*	*Provenance*	*Current location*	*Distance (km)*	*Demand time*	*Departure time*	*Arrival time*
0002-525-1-X	Cement	Portland, Ordinary 525#	Standard bag	x	X	HK	(x, y)	x.x	xx:xx xx/xx/xxxx	xx:xx xx/xx/xxxx	xx:xx xx/xx/xxxx
0201-003-1-Y	Sand	3 mm particle diameter	Cubic meter	x	Y	AU	(x, y)	x.x	xx:xx xx/xx/xxxx	xx:xx xx/xx/xxxx	xx:xx xx/xx/xxxx

Table 4.12 Real-time M&E information for crew IRP

Crew ID	*Crew name*	*Material ID*	*Material name*	*Unit*	P_i	$Q_i(j)_{es}$	$Q_i(j)_{de}$	$Q_i(j)_{re}$	$\Delta Q_i(j)$	$C_i(j)$	*Current* $Q_i(j)_{storage}$	*Demand time*
586-01-0208-010	Concretor	*0002-525-1-X*	Cement	Standard bag	x.xx	x.x	x.x	x.x	x.x	x.x	x.x	xx:xx xx/xx/xxxx
586-01-0208-010	Concretor	*0201-003-1-Y*	Sand	Cubic meter	x.xx	x.x	x.x	x.x	x.x	x.x	x.x	xx:xx xx/xx/xxxx