DEVELOPMENT OF CONSTRUCTION WASTE INDICES IN MALAYSIA

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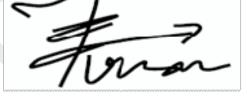

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*Specially dedicated to my beloved wife, **Fitaha Aini Fadhil**, for her everlasting love, care, patience, and encouragement. My parents, **Sam'an Malik Masudi** and **Ninin Sukminingrum**, for their endless support and advices. My dearest and cheering son, **Ahmad Faiq Firman Masudi**, for happily growing up during the completion of this thesis. And my beautiful and precious daughter, **Fakhira Zahrani Firman Masudi**, who was born shortly after the completion of my Viva Voce.*

ABSTRACT

Construction waste can be considered as one of the main factors that can give serious environmental impacts. High demand of infrastructure and building projects implementation, especially in the commercial and housing building, become the main contributors for construction waste generation in Malaysia. There is a need for Malaysian construction industry to strive for the establishment of benchmark figures and strong database for national construction waste generation and its associated impacts. The objectives of this study are: to identify the benchmark value for the extent of wastage (wastage level and waste index), carbon footprint index (CFI), and eco-costs/value ratio (EVR) as indicators for environmental loads (global warming impact) and environmental burden prevention cost in Klang Valley. Five projects in Klang Valley constructed between 2009 through 2010 had been selected for this study, which mainly include institutional, residential, and commercial building projects conducted by a wide range of contractors employing conventional and Industrialized Building System (IBS) systems. Major waste that generated at significant amount, such as concrete, timber, reinforcement bars, bricks & blocks, tiles, and plaster/mortars were taken into account. Only waste generated from construction activities at superstructure-phase was considered. Data used for the study was collected in three ways: interviews with key personnel, observational site visits, and reviews of project documentation. Benchmark for waste index for chosen sites shall fall between 0.0339 - 0.1497 m^3/m^2. Benchmark wastage levels for each specified material should fall around an average of 5 – 6 % and up to as high as 10%, except for timber. Waste index are merely governed by the waste management practice performed, type of building, size, and cost of the respected project. Benchmarks for wastage CFI shall range between 21 – 26 kg CO_2/m^2 for typical conventional projects and it shall be less for full IBS projects. Benchmarks for wastage EVR benchmarks shall fall between 0.0024 – 0.0028 for typical multi-storey projects and less for composite or full-extent IBS projects. Construction method, waste management, and type of building play a major role in CFI and EVR outcomes. Low-end projects tend to generate less waste index due to minor size and cost of the building, but not necessarily produce lower impacts. Residential and fully IBS project are proven to be the most sustainable, in terms of impacts. However, only small portion of demands are in favors for this type of project as they can be categorized as high-end (high-cost) projects. These multi-indicators assessments shall provide comprehensive and integrated evaluations for consequences and environmental loads of construction waste generation. Results of this study illustrate that the baseline figures are highly contrast and scattered, which show inconsistencies of sustainability level demonstrated among construction players. For that reason, benchmark figures shall be established by authorities and shall be achieved by construction players. Construction players shall put more emphasize on “designing-out” waste, rather than focusing on “end-of-pipeline” waste management. Implementation of IBS system was concluded as the most effective measures to minimize extent of wastage and associated impacts/losses resulted from construction waste generation as proven in this study.

ABSTRAK

Bahan buangan pembinaan boleh dianggap sebagai salah satu faktor utama yang boleh memberi kesan serius terhadap alam sekitar. Permintaan yang tinggi terhadap pelaksanaan projek-projek infrastruktur dan bangunan terutamanya di bangunan komersial dan perumahan menjadi penyebab utama bagi penjanaan sisa pembinaan di Malaysia. Terdapat keperluan untuk industri pembinaan Malaysia dalam usaha untuk penubuhan nilai penanda aras (*benchmark*) dan pangkalan data yang kukuh untuk penjanaan sisa pembinaan nasional dan kesan alam sekitar yang terkait. Objektif kajian ini adalah untuk mengenal pasti nilai penanda aras bagi aras pembaziran, indeks sisa, indeks pelepasan carbon (CFI), dan *Eco-Costs/Value Ratio* (EVR) sebagai petunjuk untuk beban alam sekitar (kesan pemanasan global) dan kos pencegahan beban alam sekitar di Lembah Klang. Lima projek di Lembah Klang yang dibina pada tahun 2009-2010 telah dipilih untuk kajian ini. Kebanyakan projek termasuk projek-projek bangunan institusi, kediaman dan komersial yang dijalankan oleh pelbagai kontraktor dengan menggunakan sistem konvensional dan sistem binaan berindustri (*Industrialized Building System-IBS).* Jenis sisa utama yang dijana pada kuantiti besar, seperti konkrit, kayu, besi tetulang, bata, jubin, dan plaster diambil kira. Namun, sisa yang dihasilkan daripada aktiviti pembinaan di fasa superstruktur sahaja yang diambil kira. Data yang digunakan untuk kajian telah dikumpulkan dalam tiga cara: wawancara dengan kakitangan utama, pelawatan tapak, dan ulasan dokumentasi projek. Penanda aras kepada indek sisa untuk tapak yang dipilih adalah di antara 0.0339-0.1497 m^3/m^2. Penanda aras tahap pembaziran bagi setiap bahan ditentukan sekitar purata 5-6% sampai dengan 10%, kecuali kayu. Indek sisa adalah semata-mata dikawal oleh amalan pengurusan sisa yang dilaksanakan, jenis bangunan, saiz, dan kos projek. Tanda aras untuk nilai CFI sisa berkisar di antara 21-26 kg CO_2/m^2 bagi projek-projek konvensional am dan nilainya lebih kecil bagi projek-projek IBS penuh. Penanda aras untuk EVR sisa berkisar antara 0.0024-0.0028 untuk projek-projek aras tinggi am dan lebih kecil untuk projek IBS komposit atau penuh. Kaedah pembinaan, pengurusan sisa, dan jenis bangunan memainkan peranan penting dalam hasil CFI dan EVR. Projek kos rendah cenderung untuk menghasilkan sisa indeks yang kecil kerana saiz dan kos yang kecil, tetapi tidak semestinya kesan akan lebih rendah. Projek kediaman dengan sistem IBS penuh terbukti paling baik, dari segi kesan terhadap alam sekitar. Walau bagaimanapun, permintaan bagi jenis projek cenderung kecil kerana mereka boleh dikategorikan sebagai projek-projek kos tinggi. Penilaian multi-indikator dapat menyediakan penilaian komprehensif dan bersepadu untuk kesan dan beban alam sekitar akibat sisa pembinaan. Keputusan kajian ini menggambarkan bahawa angka-angka penanda aras sangat ketara dan bertaburan, menunjukkan ketidakselarasan tahap kemampanan yang ditunjukkan di kalangan kontraktor. Oleh itu, penanda aras bagi pelbagai indikator ini hendaklah dikukuhkan oleh pihak berkuasa sebagai acuan yang wajib dicapai. Kontraktor hendaklah memberikan penekanan lebih kepada "merekabentuk" untuk menghapuskan penjanaan sisa, bukannya memberi tumpuan kepada pengurusan sisa di "hujung paip". Pelaksanaan sistem IBS dapat disimpulkan sebagai langkah yang paling berkesan untuk mengurangi takat pembaziran, impak, dan kerugian akibat penjanaan bahan sisa pembinaan seperti yang terbukti dalam kajian ini.

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CHAPTER 1

INTRODUCTION

1.1 Background

Malaysia's rapid economic growth and its aspiration to become a developed and industrialized nation, which is supported by the concept of "Economic Transformation" announced by the Prime Minister, have triggered and stimulated growth in development of the construction industry. The construction industry plays an important role in establishing the infrastructure required for socio-economic development and directly contribute to economic growth. The construction sector annual average growth rate under the 9th Malaysian Plan (2006-2010) was at 4.4% and expected to reach 6.7% by 2012 (Economic Planning Unit, 2012). The 10th Malaysia Plan (2011-2015) recognized that the construction sector will rise from active property market and accelerated development of infrastructure project. With continuous improvements in the Malaysian construction business environment, the market has attracted many new players. With the ever increasing volume of solid waste in Malaysia and scarcity of land in urban area where majority of construction and demolition activities take place, waste disposal problem is becoming serious due to depleting landfill area and serious environmental impact. Furthermore, Construction and Demolition (C&D hereafter) waste is generated in large quantity and their recycling are uncommon.

Construction waste can be considered as one of the main factors that can give serious environmental impacts. The construction industry is associated with high energy consumption, resource depletion, and large amount of waste generation (Kim *et al.*, 2005). The industry is one of the biggest environmental polluters (Yahya and

Boussabaine, 2006). High demands of infrastructure and building projects implementation, especially commercial and housing buildings, becomes the main contributors for construction waste generation in Malaysia (Begum *et al.*, 2009a). Therefore, construction waste management is an important issue that should be emphasized in Malaysian construction industry. Inappropriate waste disposal will give adverse impact to the environment such as excessive utilization of minerals, soil contamination, forest clearing, landslide, and flash flood. Minimizing the impacts of construction is a continuous professional and social concern in promoting sustainable development (Hendrickson & Horvath, 2000). Malaysian construction industry must thrive to reduce waste and associated impacts to sustainable level. Thus, there is an urgency to quantify and assess the environmental impact of waste generated from construction activities (Yahya and Boussabaine, 2006).

1.2 Problem Statement

The first step in construction waste minimization is to characterize and quantify the amount and composition of construction waste generated for a sound and adequate management (Jalali, 2006; Martinez-Lage *et al.*, 2010). According to Jalali (2006), waste management decisions were often based on cursory observations, guesses, and simplified inferences by site managers. Usually, waste is estimated around 5-10% of materials ordered, while true amount and type of waste remains unknown (Bossink and Brouers, 1996; Poon *et al.*, 2001b, 2009; Jalali, 2006). Quantification provides a necessary tool for evaluating the true size of the waste and hence, making the adequate decision for their minimization and sustainable management (Poon *et al.*, 2001b; Jalali, 2006; De Silva, 2008). Waste quantification is employed for the purpose of assessing environmental performance of construction project (Poon *et al.*, 2001b; Lau, 2008). The importance of this indicator is the standard baseline value or benchmark for environmental performance of contractors. Thus, the outcome can be used as a basis in decision-making that incorporates environmental considerations in construction planning, design, and operation stages as established benchmark shall also assist relevant parties or stakeholder in their planning and design stage for future projects (Jalali, 2006). The author also stressed-out that lack of benchmarking will hinder the implementation of more sustainable and innovative practices in industry. For example, country like Hong Kong has established such benchmarking as the so-called "construction waste index" term. Poon *et al.* (2001b) stated that waste index calculations can anticipate the quantity of waste that may arise, in order to establish awareness of waste minimization, to develop good planning on resources and environmental management and to reduce the wastes generated during all stages of construction project.

Meanwhile, Life Cycle Assessment (LCA) is one of the most comprehensive and accurate tool for quantitative analysis of environmental impacts over all life cycle stages of products' life. Despite the merit, LCA has been criticized as taking too much time and cost (Kim *et al.*, 2005). Simplified LCA has been applied for conducting quantitative analysis by reducing the complexity of product system boundary relevant to particular goal of LCA study (Lee *et al.*, 2004). Global warming impact is quite popular issue nowadays and this shall be emphasized which reflected by carbon emission as the single indicator of LCA analysis. Meanwhile, another latest breakthrough in LCA analysis is the eco-costing concepts which assess environmental impacts as marginal prevention costs (Vogtlander *et al.*, 2001). Vogtlander *et al.* (2001) defines eco-costs as the costs of prevention measures, which are required to reduce current emissions to a sustainable level. Eco-costing can evaluate the financial consequences of environmental impacts due to construction waste generation.

Currently, standard practice for waste quantification, simple impact assessments, or their benchmark values for Malaysian construction industry are yet to be established. From recent surveys among contractors in Klang Valley area, initial findings suggest that there are no fixed waste and material accounting practice for each site, even for projects under the same contractor. It is believed that some smaller contractors even do not keep proper waste disposal records, let alone environmental assessment records. The construction industry is considered as fragmented because policy and guidelines implementation and practice, especially regarding waste management, are inconsistent among the players. Formally-standardized system to record quantitative data is essential. Enforcement is vital to ensure that the requirements and standards are fulfilled. Authorities will benefit the annual estimates acquired from accessible database for predicting the lifespan of existing yet depleted landfills area in Malaysia, or assessing the feasibility of C&D waste recycle program. Nevertheless, local authorities are generally unwilling to make changes in local building regulations that require time and cost to establish the legislative, structural planning, and economic condition for industrial development.

Researchers used different approaches and assumptions to develop waste quantification methods that suitable with their studies (Poon, 2001b; Fatta *et al.*, 2003; Hsiao *et al.*, 2002; Cochran *et al.*, 2007). Nevertheless, there are still lacks of publications concerning C&D waste quantification and impact assessments for Malaysian context. Studies concerning construction waste for Malaysian context are mainly focused on policies, and human factor aspects of construction waste management as presented by Begum *et al.* (2007, 2009a, 2009b). More technical approach is required by catering the need for benchmarking of waste generation rate (such as waste index indicator), thus, complementing previous studies in order to achieve a more sustainable construction industry.

In addition, prefabrication or Industrialized Building System (IBS hereafter) is popularly recognized as the solution for minimizing construction waste generation, whereby metal panel formwork, precast concrete elements and/or other manufactured building components are utilized instead of conventional temporary timber formwork, in-situ concreting, and wet trades which generate large amount of waste (Poon, 2001b). Nowadays, Malaysian construction industry is undergoing transitional change from conventional system to IBS (Mokhtar and Mahmood, 2008). Nevertheless, further studies must be carried on to quantitatively assess the effectiveness of IBS in terms of waste minimization.

Based on the highlighted facts, it is believed that Malaysian construction industry needs to strive for the establishment of benchmark figures and strong database for national construction waste generation and its associated impacts. Lack of updated data could hinder Construction Industry Development Board (CIDB hereafter) as policy-maker in formulating sustainable policy, regulations and guidelines. This is reflected on the facts that there is lack of policy or regulation on construction waste management, poor enforcement, and low usage of IBS in Malaysia as compared to developed nations (Badir *et al.*, 2002; Lim, 2006; Begum *et al.*, 2007, 2009a; Nitivattananon and Borongan, 2007).

1.3 Research Boundaries

This study is undertaken to provide benchmarks and initial evaluation on generation of construction waste and associated impacts in application with various construction systems and types of building. Construction waste is considered as solid waste that eventually disposed off at landfills. Benchmarks achieved can be used as one of the indicators for sustainability of construction projects. The benchmarks shall affect the waste management practices and proper selection of construction technology among players, particularly in Klang Valley, where most of construction activities take place. Klang Valley is Malaysia's most populated urban area which is mainly Kuala Lumpur Metropolitan area. This urban area of 7.2 million people has had the most rapid development in recent years. This study will consider residential, institutional, and commercial projects employing various construction methods. Major waste generated in significant amount, such as concrete, timber, reinforcement bars, bricks & blocks, tiles, etc were taken into account. Only waste generated from construction activities at superstructure-phase was considered. Hazardous waste was not considered in the scope of this study. Demolition, refurbishment, and civil engineering / infrastructure projects were not considered due to their limited number of on-going projects and lack of available data. A number of on-going construction projects in Klang Valley were sampled as case studies which represent the overall characteristics of waste generation and associated impacts, mainly based on their construction method and type of building.

1.4 Research Aim and Objectives

The aim of this study is to identify the benchmark values for the extent of wastage and associated impacts (global warming impact and environmental burden prevention cost) due to construction waste generated from various types of projects in Klang Valley employing various construction methods. These benchmarks can be applied as reference for future projects in assessing environmental performance, thus, improving waste management practice and waste minimization awareness among construction players. The objectives of study are as follows:

Objectives of Study

i) To quantify and compare waste indices from selected projects.

ii) To quantify the wastage level for major construction materials from selected projects.

iii) To quantify and assess the carbon footprint index (equivalent kg of CO_2/Gross Floor Area) resulted due to construction waste generated from selected projects.

iv) To quantify and assess the eco-costs/value ratio (EVR index) resulted due to construction waste generated from selected projects.

1.5 Scope of Research

i) This study focused on wastage level, waste index, carbon emissions and eco-costs for waste generated during construction phase only, not the full life cycle of building.

ii) Major waste materials such as concrete, timber, reinforcement bars, bricks & blocks were considered. Hazardous waste was not included in the scope of study.

iii) Waste generated from construction activities at superstructure phase was taken into account. Waste generated from substructure and foundations works are considered very minimum which consists of mostly soil. Soil is considered valuable commodity and can be sold.

iv) Various types of projects (residential, commercial, and institutional buildings) employing conventional and IBS systems in Klang Valley.

1.6 Research Outputs

The research contributions are as follow:

1. Waste Index, wastage level, carbon emission index, and EVR index benchmark values as environmental performance indicators and standards for Malaysian construction industry.
2. Full data analysis and statistical correlations among assessment tools.

3. Templates for establishing reliable database associated with environmental performance for Malaysian construction industry.

1.7 Benefits of Research

The benefits are as follow:

For contractors:

1. Financial benefit through savings on disposal cost, material loss, and other indirect costs.
2. Sound and adequate standardized waste quantification as performance indicator to instill environmental awareness.
3. Anticipate waste that may arise, develop good planning on resources and reliable Waste Management Plan (WMP) to ensure that benchmark targets can be met.
4. Basis in decision-making that incorporates environmental considerations in construction planning, design, and operational stages. Established benchmarks shall also assist in planning and design stage for future projects.
5. To help decision-making for choosing the most suitable and cost-effective construction system in terms of environmental impacts generated.
6. Encouraged to pursue relevant “green” certifications which provide comprehensive assessment framework and guidelines in order to improve company’s reputation and image.
7. Benchmarks can be announced publicly as part of Corporate Social Responsibility.

For authorities:

1. To trace potential environmental impacts of construction debris generation.

2. Estimate regional and national C&D generation rate for predicting the lifespan of existing landfills, and as a basis in formulating and implementation of policies to reduce environmental impacts by the construction sector.
3. Save budget for opening new landfill area; spare land which can be used for other purposes indirectly assists national socio-economic growth
4. Formulate policies & regulations to assess and evaluate environmental performances, audit, and evaluation of contractors based on environmental benchmark requirements.
5. Formulate standardized construction waste record-keeping method and format for reliable access of data and ease evaluation process.
6. Encourage the usage of IBS to contractors. Help to create new market and business potential for local IBS precasters, thus, increasing the maturity of IBS in Malaysia.
7. To make certain certifications or provisions (ISO 14001, GBI rating system, WMP development, and other related provisions) to be mandatory, in favor of a more sustainable construction industry.
8. Assess the feasibility of construction waste recycling program while promoting to create new business and job opportunities.

National Impacts:

1. More sustainable Malaysian construction industry by reducing environmental impacts, reduction of opening new landfills, preserving available natural resources, and prolonging the lifespan of existing landfills.
2. Authorities are expected to formulate reliable policies and regulation with thorough enforcement in order to instill environmental awareness, promote sustainable management, better and more responsible practices among relevant construction parties and stakeholders.

1.8 Limitations of Study

The limitations of this study are as follow:

1. Commitment with the industry.

   Unwillingness and lack of interest shown by the industry to participate in data collection process resulted in a small number of project case-studies.

2. Confidentiality issue.

   In line with commitment issue, confidentiality was also the main reason for lack of supports and unapproachable attitudes toward this research, particularly data collection.

3. Various construction progresses or stages.

   Each contractor participated had various projects in hand with various completion stages. Due to practicality of data collection, it was preferable to focus on projects which were at "almost completion" stage (more than 80% progress) during data collection.

4. Timing factor.

   Since construction projects may take up to two years in completion, monitoring the progress of each project from early development until 100% completion was time-consuming, tedious, and unrealistic.

5. Poor record-keeping practice among contractors.

   This had resulted in minimum numerical data (particularly Bill of Quantities) retrieved for data analyses processes, which presented in non-uniform formats or units of quantity among various contractors and projects. Some degree of assumptions and unit conversion were necessary to perform in order to carry out calculations and data analyses.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter mainly discusses: the definition of construction waste; construction waste generation and characteristics in various countries; construction waste by categories; source evaluation and problems associated with generation of construction waste, waste management towards waste minimization, conventional construction method, IBS construction method, waste quantification, and environmental impacts quantification.

2.2 Definition of Construction Waste

Construction waste is defined as:

> "The by-product generated and removed from construction, renovation and demolition workplaces or sites of building and civil engineering structured" (Cheung, 1993).

Similarly, Skoyles and Skoyles (1987) has defined building waste as the difference between materials ordered and those placed for fixing on building projects.

Hong Kong Environmental Protection Department (EPD) defines Construction and Demolition Materials as:

> "a mixture of surplus materials arising from any excavation, civil/building construction, site clearance, demolition activities, road works and building renovation".

For the purpose of source evaluation of construction waste, Ekanayake and Ofori (2000) have given a broader definition of construction waste as:

> "Any material, apart from earth materials, which need to be transported elsewhere from the construction site or used within the construction site itself for the purpose of landfilling, incineration, recycling, reusing or composting, other than the intended specific purpose of the project due to material damage, excess, non-use, or non-compliance with the specifications or being a by-product of the construction process".

The aforementioned authors reported that examples of construction waste are concrete, mortar, bricks, excessive wood, piping materials, metal and demolition waste. Poon *et al.* (2001b) reported that over 80% of C&D materials are inert and will be ended up as public fills, including debris, rubble, earth and concrete which are suitable for land reclamation and site formation. The remaining is non-inert waste such as timber. Figure 2.1 shows a typical view of C&D waste.

Figure 2.1 Constructions and Demolition Waste

2.3 Construction Waste Generation and Characteristics

According to Ferguson, *et al.* (1995), construction waste can account for more than 50% of landfill area. 17 % of total waste production in UK comprises of C&D waste, which is about 70 million tones or about 24 kg/week/person (four times the amount of household waste). This makes C&D waste as the largest generation of controlled waste, as shown in Figure 2.2 (Coventry *et al.*, 2001). According to Act No. 672 of the Malaysian Solid Waste & Public Cleansing Management Act (2007), controlled solid waste is defined as: "any solid waste falling within any of the following categories: (a) Commercial solid waste; (b) Construction solid waste; (c) Household solid waste; (d) Industrial solid waste; (e) Institutional solid waste; (f) Imported solid waste; (g) Public solid waste; or (h) solid waste which may be prescribed from time to time.

Over 2 billion tonnes of waste are generated in the European community each year, of which approximately 500 million tonnes are produced in UK (Coventry *et al.*, 2001).

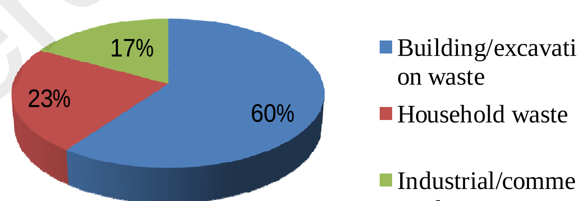


Figure 2.2 Typical Landfilled Waste Composition in UK (Source: Ferguson *et al.*, 1995)

In 2001, 44% of solid waste disposed at municipal landfill sites in Hong Kong is C&D waste (Poon*et al.*, 2001a). C&D waste has been taking up valuable landfill space at a rate of more than 3,500 m^2 per day. It is also estimated that generation of C&D waste in Greece is more than 2.6 million tonnes in 2000 (Fatta *et al.*, 2003). Between 2002 until 2005, characterization showed that 1.1 million tonnes of construction waste are generated in Thailand (Gheewala and Kofoworola, 2009).

As landfill sites are becoming scarce, the cost of disposing construction waste is likely to rise. C&D waste disposed at landfill in various countries is presented in Table 2.1.

Table 2.1 Comparison of C&D Waste at Landfills in Various Countries

Country	Concentration of Construction waste in total waste (in %)	C & D waste recycled (in %)	Sources
Australia	44	51	Hendriks and Pietersen (2000)
Brazil	15	8	Hendriks and Pietersen (2000)
Denmark	25-50	80	Hendriks and Pietersen (2000)
Finland	14	40	Construction Materials Recycling Association (2005), Hendriks and Pietersen (2000)
France	25	20-30	Construction Materials Recycling Association (2005), Hendriks and Pietersen (2000)
Germany	19	40-60	Construction Materials Recycling Association (2005), Hendriks and Pietersen (2000)
Hong Kong	38	No Information	Hong Kong Government – Environmental Protection Department (2006), Poon (2000)
Japan	36	65	Construction Materials Recycling Association (2005), Hendriks and Pietersen (2000)
Italy	30	10	Construction Materials Recycling Association (2005), Hendriks and Pietersen (2000)
Netherland	26	75	Construction Materials Recycling Association (2005)
Norway	30	7	Hendriks and Pietersen (2000)
Spain	70	17	Hendriks and Pietersen (2000)
UK	Over 50	40	Hendriks and Pietersen (2000)
USA	29	25	Construction Materials Recycling Association (2005), Hendriks and Pietersen (2000)
Malaysia	NA	NA	NA

(NA: Not Available)

2.4 Classification of C&D Waste

In general, C&D waste is categorized in a variety of ways, and each category produces waste with different composition and characteristics. Thus, different construction activities performed (i.e. construction, demolition, refurbishment) will generate waste with different characteristics. For example, C&D waste generated from infrastructure projects such as bridges and road differs from that of building waste. Infrastructure projects generate large quantity of waste with just a few waste materials (mainly asphalt and concrete), while building projects generate more variety of waste materials with different portions. According to Franklin Associates (1998), the amount of C&D debris generated in any region or nation is influenced by: the general economic conditions of the vicinity; the weather; major disasters; special projects; and local regulations. Poon *et al*. (2009) agreed with the mentioned finding and concluded that the amount and type of C&D waste depends on: type of projects; size of the projects; and construction technology employed.

Studies have shown that construction activities were closely related to the amount of waste generated (Poon and Jaillon, 2004). C&D waste can be classified according to type of works or activities performed from which it is generated. There are five types of works which were identified in past study commissioned by the Hong Kong Environmental Protection Department (Poon *et al*., 2001b) as shown in Figure 2.3.Hong Kong EPD had also identified 12 sub-categories of waste constitute the bulk of C&D waste received at landfills which is indicated in Table 2.2.

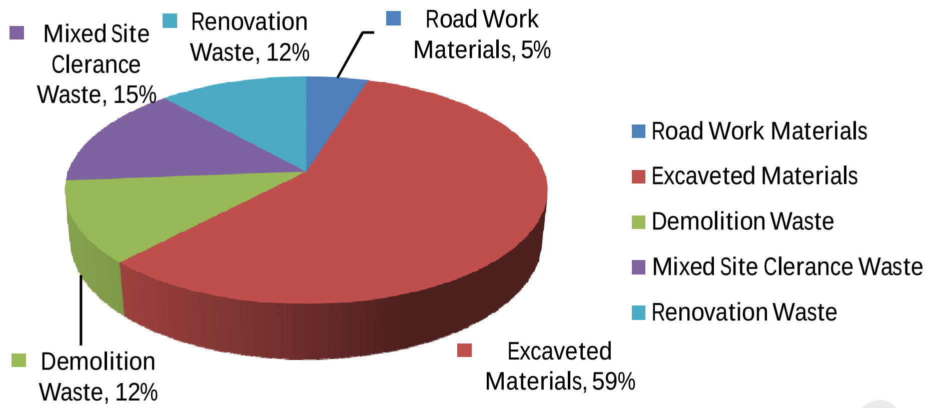


Figure 2.3 C&D Waste According to Activities Performed (Source: Poon *et al.*, 2001b)

Table 2.2 Composition of Each Category of C&D waste (Source: Poon et al., 2001b)

Component	**Composition of each category of C&D waste received at landfill sites (% by weight)**				
	Road work material	**Excavated soil**	**Demolition waste**	**Site clearance**	**Renovation waste**
Soil/Sand*	23.0	73.8	21.5	33.0	19.4
Concrete/Mortar*	16.9	1.2	10.8	4.6	7.4
Rock/Rubble*	14.4	12.5	27.7	15.0	38.8
Reinforced concrete*	14.2	0.4	5.8	0.9	7.0
Bricks/Tiles*	0.8	0.4	12.1	1.4	9.6
Slurry & mud	1.8	9.7	1.5	1.0	3.1
Asphalt	24.7	0.0	0.0	0.2	0.0
Cement contaminated	1.7	0.4	3.2	15.6	3.3
Wood	0.6	0.9	10.5	13.3	7.1
Ferrous metals	0.5	0.0	0.6	1.0	1.3
Non-ferrous metals	0.0	0.0	0.7	0.2	0.1
Others (include bamboo, glass, plastics, bulky waste, organics & garbage	1.4	0.7	5.6	13.8	2.9
Total	**100**	**100**	**100**	**100**	**100**
Percentage of total quantity of C&D waste landfilled	5.2	59.4	8.5	14.6	12.3

Note: * Inert materials which are considered suitable for public filling area

2.5 Construction Waste Source Evaluation

For new building construction, there are two main types of waste, structural waste and finishing waste (Skoyles and Skoyles, 1987). Concrete fragment, reinforcement bars, abandoned timber plate and pieces are generated as structural waste during the course of project. Finishing waste is generated during finishing stage or wet trades, such as plastering, screeding, and tiling. For instance, surplus cement mortar scatters arising from screeding. Damaged materials like tiles, ceramics, paints, and plastering materials are wasted because of mishandling. Packaging is also considered as part of finishing waste.

Poon and Jaillon (2004) reported that, based on phase of building construction, timber formwork during super-structure phase is the main contributor of waste, contributing up to 30% of all waste identified. Wet trades during finishing work such as screeding, plastering, and tiling were identified as the second major waste contributor, at 20%. Gavilan and Bernold (1994) had developed a broad generation model that overview the material-flow of construction process waste.

While material-flow model presents a basic overview, Gavilan and Bernold (1994) also identified conceptual framework that organizes source identification of construction waste which can be categorized as:

1. Design (blueprint error, detail error, design changes)
2. Procurement (shipping error, ordering error)
3. Material Handling (improper storage/deterioration, improper handling
4. Operation (human error, equipment malfunctions, acts of God (catastrophes, accident, and weather)
5. Residual (leftover scrap, unreclaimable nonconsumables)
6. Others

The authors concluded that most of construction waste is generated from mainly two sources, leftover cutting stocks, and nonreusable nonconsumable stocks. Consumable stocks are materials that are part of the structure, such as bricks or concrete. While nonconsumable stocks refer to material that aids construction process, such as timber for formwork. Dainty *et al.* (2004) agrees with the previous findings and concluded that there are positive links between good site management with productivity, waste reduction, and safety performance.

Other authors (Bossink and Brouwers, 1996; Ofori and Ekanayake, 2000a, 2000b; and Poon *et al.*, 2001b) agreed with the framework of construction waste source categories as suggested by Gavilan and Bernold (1994).Empirical study conducted in Shenzhen found that most sources of construction waste originated from formwork, finishing work, cut-off, and mishandling (Tam *et al.*, 2008; Lu *et al.*, 2011), whereas Faniran and Caban (1998), Dainty *et al.* (2004), and Ofori and Ekanayake (2000a, 2000b) reported that design changes and leftover scrap are two of the most frequent causes of construction waste generation in New South Wales (Australia) and Singapore, respectively. Similarly, according to Poon *et al.* (2004), design variation occurs due to: (1) last minute client requirement, (2) complex design, (3) lack of communication, and (4) lack of design information. Thus, effective communication and interaction is crucial in avoiding design problems as well as standardization of dimension, careful attention in design, and detailed planning (Faniran and Caban, 1998).

In general, Poon and Jaillon (2004) concluded that the causes or sources of waste on building projects can be broadly divided into two groups: (1) work processes and (2) poor material handling in non-working phase.

For group (1), it was expected that waste can be generated from trades that require high level of labor skill such as plastering. For group (2), it is arisen from damage and loss of material due to poor design, during transportation, storage, and other material handling processes. A list of extended and more detailed list of sources and causes of construction waste generation from previous studies are presented in Table 2.3.

Table 2.3 Causes and Examples of Building Waste on Site in Hong Kong (Source: Poon & Jaillon, 2004)

Causes of Building Waste on Site		Examples
Site Management and Practice s	- Lack of a quality management system aimed at waste minimization	e. g. lack of waste management plan
	- Untidy construction sites	e. g. waste materials are not segregated from useful materials
	- Poor handling	e. g. breakage, damage, losses
	- Over-seized foundations and other elements	e. g. finished concrete staircases are not protected by boarding
	- Limited visibility on site resulting in damage	e. g. pallet is not used to protect cement bags from contamination by ground water
	- Poor storage	e. g. pallet is not used to protect cement bags from contamination by ground water
	- Poor workmanship	e. g. poor workmanship of formwork of formwork
	- Waste generation inherited with traditional construction method	e. g. timber formwork, wet trade
Delivery of Products	- Over-ordering	e. g. over ordering of concrete becomes waste
	- Method of packaging	e. g. inadequate protection to the materials
	- Method of transport	e. g. materials drop from forklift
	- Inadequate data regarding time and method of delivery	e. g. lack of records concerning materials delivery

Recent studies indicate that approximately 5-10% of building materials shall end up as waste on building sites (Poon *et al.*, 2001b). Poon and Jaillon (2004) described their finding for percentage wastage of various trades for public and private residential projects in Hong Kong (Table 2.4). In addition, Bossink and Brouwers (1996) also reported that between 1% to 10% (averaged 9%) of purchased materials will likely to end up as waste. These estimations will be later utilized for the establishment of 'wastage level' concept approach, as can be found in sub-chapter 2.9: Waste Quantification Model.

Table 2.4 Typical Causes and Disposal Level of Building Waste Generated from Various Trades in Hong Kong (Source: Poon et al., 2004)

Site Activities	Material Generated	Cause of Wastage	Wastage Level (vol. %)*	Total Disposal Level (vol. %) *	Recovery Level (vol. %) *
Timber formworking	Timber broad	Cutting scrap Striking of formwork	3 47	50	50
Metal formworking	Steel	Striking of formwork	0	0	100
Reinforcement fixing	Steel bars	Cutting scrap Abortive work (e. g. drawing modified by structural engineer)	0.5 0.3	0.8	3.7
In-situ concreting	Concrete	Left over on the truck after unloading Trial panel Slump test Left over	0.7 0.4 0.7 0.7	2.5	2
Bricks & Blocks work	Bricks	Cutting waste Damage due to improper stacking during storage stage Damage due to careless handling of workers during bricks and blocks work Abortive work	2 0.2 0.2 0.5	2.9	NIL
Dry wall	Light weight concrete	Excessive ordering Damage due to careless handling of workers during unloading stage Damage by workers during storage at working levels Cutting waste	1 0.1 0.1 1.8	3	NIL
Wall and floor screeding	Ready-mix cement, on site mix cement	Broken bags due to careless handling of workers during unloading stage Broken bags due to improper stacking during storage stage Broken bags due to careless handling of workers during transportation to working levels Left-over Lost while applying Abortive work-Debonning	0.35 0.35 0.35 1.6 1 2.5	6.15	NIL
Wall and floor	Plaster	Broken bags due to	0.4	2.9	NIL

Site Activities	**Material Generated**	**Cause of Wastage**	**Wastage Level (vol. %)***	**Total Disposal Level (vol. %) ***	**Recovery Level (vol. %) ***
plastering		careless handling of workers during unloading stage Broken bags due to improper stacking during storage stage Broken bags due to careless handling of workers during transportation to working levels Lost while applying Over-mixing	0.5 0.5 0.6 0.9		
Floor and wall tiling	Tiles	Damage due to careless handling of workers during unloading stage Damage due to improper stacking during storage stage Damage due to careless handling of workers during transportation to working levels Cutting waste Abortive work after quality checking (e.g. cracking due to poor workmanship)	0.35 0.35 0.35 2.75 1.5	5.3	NIL

2.6 Waste Management Towards Construction Waste Minimization

2.6.1 Waste Management Plan (WMP)

Studies by Poon and Jaillon (2004), and Tam (2008) have shown that 'cost' and 'completion time' are the most important project's goal and the major factors that affect construction method and material selection. Most of respondents in the respected studies pointed out that 'environmental concern' is the least important factor as shown in Table 2.5 (Tam, 2008). Poon *et al.* (2004) also reported that there were no significant difference noticed between contractors implementing Environmental Management System (EMS), i.e. ISO14001 certification and contractors without in their waste management practices. Among the benefits of EMS implementation by contractors are awareness improvement, and fulfillment of regulations. Nevertheless, the aforementioned stated that not all contractors that practice this achieve legal requirements or manage their waste in environmentally manner because higher cost is required for proper management (Rodroguez *et al.*, 2007).

Urio and Brent (2006) also pointed out that poor waste management leads to direct financial losses; hazardous environmental impact; and hampers national waste minimization efforts. According to Poon *et al.* (2004), Waste Management Plan (WMP hereafter) thoroughly deals with waste issue, making it the first step to identify whether potential waste problems exist. Consequently, WMP can trigger environmental awareness among construction personnel.

Table 2.5 Contractors' Project Priority (Source: Tam, 2008)

Project goal of construction projects	Most Important (%)	Least important (%)
Cost	39.5	5.3
Time	15.8	18.4
Quality	18.4	15.8
Environmental	0.00	47.4
Safety	26.3	13.2
Total	100.0	100.0

2.6.1.1 Waste Management Hierarchy

Commonly, a simple and comprehensive WMP hierarchy should consist of 'Avoidance', 'Minimization', 'Reuse', and 'Recycle' (Coventry *et al.*, 2001). Currently, 3R (Reduce; Reuse; Recycle) is one of the most popular waste management principles that have gained wide spread of exposure in C&D waste management in many urban areas in Asia (Nitivattananon and Borongan, 2007). Poon *et al.* (2001b) described the waste management hierarchy in Figure 2.4 below. Based on the pyramid-shaped hierarchy, 'avoidance' should come first. It implies that waste generation should be avoided in the first place. If waste generation takes place, waste reduction or minimization techniques should be employed on-site or even within design stage.

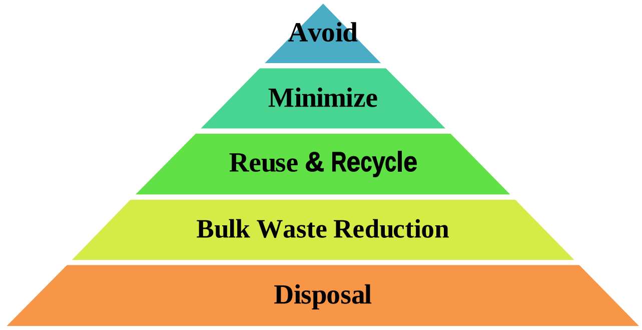


Figure 2.4 Waste Management Hierarchies (Source: Poon et al., 2001b)

Reclaiming reusable materials and waste recycling should come next, before actually dispose the remaining waste to landfills. Based on waste management hierarchy and surveys conducted by Poon *et al.* (2001a), 'source separation' should be the next action in dealing with construction waste generation. On-site sorting of C&D waste materials create better segregation of inert and non-inert waste at less effort as most of C&D waste are inert materials. Thus, on-site sorting would ease the separation of hazardous, reclaimable, and recyclable materials. However, space availability, management effort, cost, and interferences are among the hindrances of practicing on-site sorting of C&D waste materials (Poon *et al.*, 2001b).

According to Poon *et al.* (2009), WMP is vital, especially to encourage waste sorting and 3R (Reduce, Reuse, and Recycle) practices among constructors. The aforementioned also suggest that government role is essential to implement policy that require (1) establishment of WMP which encourage sorting and 3R, (2) using secondary aggregates and recycled materials, and (3) other form of incentives.

In general, a WMP lists specific waste materials and identify the amounts to be targeted for reduction, salvage, reuse or recycling with the inclusion of timeline in the plan to allow estimation of specific wastes to be generated during the entire phase of construction process (Poon *et al.*, 2004). With prior planning, waste prevention goals for specific materials can be established, as well as arrangements for its storage, reuse, transportation, and disposal. Rodriguez *et al.* (2007) stressed the importance of adopting lifecycle perspective when evaluating Waste Management (WM) measures for sustainable waste management as the application of integrated lifecycle management concept to the management of waste. According to Faniran and Caban (1998), practical waste minimization strategies require source identification, a detailed understanding of what cause waste to arise. Poon *et al.* (2004) suggested that the following aspects should be included to form the structure for waste management plan:

- Analysis of waste generated (types, quantities, time)
- Alternative to disposal (reduction, sorting)
- List of materials to be reused, salvaged, recycled
- Disposal options (public fill area or landfill)
- Material/waste handling procedures
- Designation of on-site waste management manager
- Waste sorting and landfilling facilities
- Special handling and disposal of hazardous waste

2.6.1.2 Implementing WMP

WMP implementation requires willingness to minimize waste between contractors, clients, and designers. Therefore, good coordination and communication between top management, clients, designers, and contractors are more likely to have immediate impact on reducing waste (Keys *et al.*, 2000).

Dainty *et al.* (2004) recognized that legislation is the key issue for ensuring waste management practice in many countries. They found that recently, human behavior and waste causation have a significant effect in implementing successful WMP. Heavy consideration should be put on key elements such as waste issues, audit procedure, training, and education. Therefore, waste management is now becoming a pressing issue in construction industry as the major contributor of solid waste generation. Tam *et al.* (2007b) stated that waste management needs to be implemented as part of the project objectives. Thus, it requires training and education among staff; support from management; and governmental enforcement.

2.6.1.3 Regulatory Measures in WMP

In a case study that examined the effectiveness of implementing regulatory measures for reducing construction waste in Hong Kong, Tam *et al.* (2007c) found out that it appears that the effectiveness of these measures had been limited. 'Implementation of environmental management system'; and 'implementation of waste management framework plan' are perceived as the most effective measures but still need support from clients and assist from government, by providing incentives, education, guidelines and tax reduction (Tam *et al.*, 2007c).

Other form of government support includes formulating provisions to facilitate C&D Waste Management, especially for stimulating the market for recycled materials (Rodriguez *et al.*, 2007). The results of this investigation illustrate that legal commitments have been mainly allocated to contractors. Insufficient commitment and responsibilities are allocated to other project participants such as clients, designers, consultants, and other project stakeholders. Thus, revisions and further development of legal measures are necessary (Tam *et al.*, 2007c).

2.6.2 Waste Minimization Practices

Reduction of construction waste amount generated and increase in the reuse and recycling of waste can help reducing environmental impacts, such as: waste disposal; handling and sourcing of raw materials (Construction Industry Research & Information Association - CIRIA, 2001). Reduction of waste is becoming more and more important as cost of waste disposal rises. According to Poon and Jaillon (2002), one of the issues that show the need for waste minimization is the consideration of environmental issues that becoming increasingly important in development and architecture; hence designers are required to produce more efficient and sustainable designs.

CIRIA (CIRIA, 2001) defines waste minimization as:

"Any technique, process or activity that either avoids, eliminates or reduces waste as its source or allows reuse or recycling of waste".

The followings are the benefits of waste minimization in the construction industry, which are compiled from Coventry *et al.* (2001), and Poon and Jaillon (2002):

1. Financial:
    a) Reduction of wastage of new materials through mishandling damages, over-ordering and off-cuts.
    b) Reduction of disposal cost
    c) Increase salvage value by using reclaimed materials (eg. Crushed concrete and brickwork used as filler gravel/secondary aggregates)
2. Environmental:
    a) Reduced quantity of waste generated, amount of waste disposed at landfills (which extent the lifespan of landfills), transportation of waste to be disposed of, and pollution.
    b) Promote efficient use of waste generated.
3. Business: Increased performance and management
4. Other benefits: Increased site safety, work efficiency, image of the company (e.g. BREEM, HKBEAM, LEED, Green Star certifications, or 'buildability' ratings)

It is noteworthy that landfilling and disposal cost are included as direct cost. The fact is that indirect costs are also incurred by contractors disposing waste. According to Coventry *et al*. (2001), indirect costs are consist of: capital cost of wasted materials; cost of transportation of materials waste; cost of storing, transporting, and disposing; cost of revenue which could have been achieved by reclaiming the waste materials; loss of time. Coventry *et al.* (2001) found that the ratio of indirect/direct cost for waste disposal could be as much as 100.

As previously discussed, reducing waste at the source is genuinely the most logical and economical way to 'treat' construction waste. Many studies (Gavilan& Bernold, 1994; Faniran and Caban, 1998; Coventry *et al.*, 2001; Poon and Jaillon, 2004; Poon *et al.*, 2004; Dainty *et al.*, 2004; Tam *et al.*, 2008; Tam, 2008) conclude that reducing waste is the best option in implementing Waste Management Plan.

Poon *et al.* (2001b) proposed a model to describe waste minimization techniques employed on construction sites which are based on source reduction, good on-site operating practices, and design issues.

2.6.2.1 Waste Assessments and Estimations

The first step in implementing waste minimization program is to estimate the quantity of construction waste generated (De Silva, 2008). It is a mean to estimate the quantity of C&D waste generated, and thus, assessing the potential for waste reduction. Amount and composition materials are useful information that can be employed to develop waste minimization policies (Cochran *et al.*, 2007).In the context of WMP, availability of adequate information and certain parameters such as volume and characteristic of construction waste are crucial (Gheewala and Kofoworola, 2009). Thus, a better understanding of C&D waste generation in terms of causes and sources can be achieved (Lau *et al.*, 2008; Lu *et al.*, 2011).

Poon *et al.* (2004) pointed out that waste assessment (analysis on types and quantities of waste generated) is essential part of waste management plan structure. For instance, waste estimation by employing ‘waste index’ calculation approach is essential in helping project manager to anticipate the quantities of waste that are likely to be produced in building projects (Poon *et al.*, 2001b). In the future, contractors could provide clients with waste indices of their previously completed projects as reference to promote waste minimization.

For illustration, Bossink and Brouwers (1996) stated that even though construction waste make a smaller contribution than demolition waste, it is vital to be quantified due to:

- Construction waste is more difficult to recycle due to high level of contamination and a large degree of heterogeneity;
- Prevention of construction waste is preferable to recycling of demolition waste at the ‘end of pipeline’;
- Construction waste contains a relatively high amount of chemical and hazardous waste; and
- Cost reduction is substantial.

Waste quantification and estimation methods such as ‘waste index’ approach will be discussed later on sub-chapter about waste quantification model (**sub-chapter 2.10**).

2.6.2.2 Design Issues in Waste Minimization

Poon *et al.* (2009) addressed that one should consider reducing waste since design stage of the project. The author also pointed out that reducing waste for new building project involves both design concept/building technology (employing low waste building technology such as prefabrication) and material selection. Osmani *et al.* (2008) found that about one-third of construction waste could essentially arise from design decisions. Surveys conducted by Poon and Jaillon (2004) found that most respondents had realized that design variation is responsible for significant waste generation. 'Last minute client requirements' is identified as the main cause of design changes.

2.6.2.3 Material Control and On-Site Practices

As discussed earlier, Poon and Jaillon (2004) concluded that the causes or sources of waste on building projects can be broadly divided into two groups: (1) work processes and (2) poor material handling in non-working phase. Similarly, Dainty *et al.* (2004) studied that 'poor site management' is responsible for source-generation of C&D waste in UK. Consequently, a specific term –'material control'– arises. According to Chartered Institute of Building, 'material control' may be defined as those strategies to minimize material loss or damage through good design, specification and procurement, packaging, careful transportation, reception, handling, storage, and co-ordination (Ferguson *et al.*, 1995).

Similarly, Coventry *et al.* (2001) listed out key elements for waste minimization practices on site, which include:

- Maximize the use of reused/recycled materials (e.g. recycling of crushed concrete as secondary aggregates);
- Appropriate material dimensions and employ prefabricated units;
- Efficient ordering (e.g. practice Just-In-Time delivery, avoid over-ordering);
- Good practice of handling and storage;
- Contractual arrangements that assess environmental performance and responsibility of waste management;
- Segregation/sorting of waste; and

- Waste auditing.

2.7 Waste Management in Malaysian Construction Industry

High demands of infrastructure and building projects implementation especially in the commercial and housing building becomes the main contributors for construction waste generation in Malaysia (Begum *et al.*, 2009a). Therefore, construction waste management is an important issue that should be emphasized in Malaysian construction industry. In general, C&D waste is bulky, heavy and is mostly unsuitable for disposal by incineration or composting (Nitivattananon and Borongan, 2007). The aforementioned also suggested that this situation poses waste management problems in urban areas, particularly those with depleting land area for waste disposal of which C&D waste accounts in an alarming rate. Meanwhile, illegal dumping is a common practice among contractors in Malaysia (Begum *et al.*, 2009a).

2.7.1 Policy and Regulations Aspects

Nitivattananon and Borongan (2007) stated that nowadays, government in many countries have developed laws and regulations governing 3R principles for C&D waste related to sustainable construction but, currently, its existence is minimal in Asian developing countries such as Malaysia. Although the 3R principles are generally practiced on sites, most Asian countries including Malaysia do not have specific regulations designed for C&D waste as legal system and institutional arrangements regarding 3R have yet to be established (Nitivattananon and Borongan, 2007).

Nevertheless, country like Singapore has established and practiced Environmental Management System (EMS) to attain sustainable development by audit system on its construction firms. In Taiwan, its EPA has established concrete recycling and reutilization program since 1999 (Hsiao *et al.*, 2002). While Thailand also has implemented an integrated waste management plan (WMP) and effective recycling of C&D waste to integrate recycle and energy conservation, and to create jobs (Gheewala and Kofoworola, 2009). Hong Kong can be considered as the most committed country in sustainable construction with substantial solid waste management policies such as: Construction Waste Disposal Charging Scheme; Requirements for contractors to formulate WMP; Adopt low waste construction technologies (such as IBS); Implement selective demolition; Reuse and recycled aggregates in road sub-base and low grade concrete; and Tracking system for C&D waste disposal (Poon *et al.*, 2004). Therefore, for Malaysian construction industry, the challenges are to develop and establish: waste quantification; practices and technologies; institutional set up in managing C&D waste. Table 2.6 provides comparisons on various waste management practices and status for construction industry in some Asian countries.

Table 2.6 Updated summary of C&D Waste Management in Some Selected Asian Countries (Source: Nitivattananon and Borongan, 2007)

Country	Annual C&D waste (amount or proportion of the total waste)	Strategies and Technologies	Practices	Policy and institutions
Singapore	200,000 tonnes	Recycling of construction waste into aggregates	Reduce, reuse and recycling	Building and Construction Authority (BCA) established an ISO 14000 Certification Scheme- a surveillance audit for construction firms
Taiwan	Approximately 2.4 million metric tonnes of concrete waste	Recycling Technology (Recycled concrete and aggregate)	Recycled concrete aggregate and recycled aggregate	• EPA initiated the waste asphalt concrete reutilization program in 1999 to standardize relevant quality requirement • Established the Remaining Earthwork Information Services Center
Vietnam	Construction waste and sewage sludge make up for about 8% of municipal waste	Reuse	Construction waste is normally used for back (public) filling	NA
Thailand	1.1 million tonnes	Portion of C&D waste disposed	Reduce, reuse and recycling	• Development of Construction and demolition

Country	Annual C&D waste (amount or proportion of the total waste)	Strategies and Technologies	Practices	Policy and institutions
	(Gheewala and Kofoworola, 2009)	to landfills		waste program • Investigation on recycling and reuse of Debris from the Tsunami Disaster
Sri Lanka	NA	Reuse and recycling such as door frames, bricks	Reuse and recycling industry	• Reuse and recycling has been practiced • Development of Construction Waste Management (COWAM) Centre
India	14.5 MT	Recycling and reuse of marble waste in building application	Portion of C&D waste is recycle and reuse in building materials and share of recycled materials	Ministry of Environment and forests has mandated environmental clearance for all large construction projects
Hong Kong SAR	42%	Reuse – done by selective demolition technique	Reuse of C&D waste in grade 37% - 80% public filling areas for land reclamation purposes for period 12 years	• Construction Waste Disposal Charging Scheme • Public Works Programs, the contractors are required to formulate waste management plans • Adopt low waste construction techniques, selective demolition • Reuse and recycled aggregates in road sub-base and low grade concrete • Tracking system for C&D waste disposal • Developed to a GPS-and-GIS-integrated construction M&E management system
China	17.5%	Reuse and recycling		Municipal Construction Waste regulations – Imposes stricter management on waste from municipal construction projects
Malaysia	28.34% (including industrial waste)	Reuse and recycling	Reuse and recycling	Reuse and recycling has been practiced – economic dimension

(NA: Not Available)

2.7.2 Current Practices

Study conducted by Begum *et al.* in 2007 among contractors in Klang Valley on waste minimization factors practiced in Malaysia found out that 3R is the most practiced (Table 2.7).

Table 2.7 Updated Summary of C&D Waste Management in Some Selected Asian Countries (Source: Begum *et al.*, 2007)

Waste Management Practices	Level of Practice
[buy repairable, refillable, durable materials]; [recycling]; [reusing]; [using materials before expiry date/damaged]; and [purchasing sufficient raw materials]	most practiced
[buy materials with reuse packing]; [facilitates reusing and recycling for sorting types of waste]; [exchange waste with others]; and [use less toxic materials]	fairly practiced
[employ low waste building technology]; [changing design of construction process]; and [offer education, training, reward programs]	least practiced

Contrary to waste minimization practices in some developed countries like Hong Kong (Poon *et al.*, 2001b; Nitivattananon and Borongan, 2007; Tam *et al.*, 2008; Baldwin *et al.*, 2009) where the trend on minimizing waste is now focusing on design issues (e.g. employing low waste building technology such as IBS), regulations, and human behavior (establishing education and training center). These factors are seen to be least practiced in Malaysia's waste management activities due to high cost and commitments. These could be true for short term gains but not for long-term, which is still perceived as one of the main objectives among contractors (Begum *et al.*, 2007).

Begum *et al.* (2006) reported that economic feasibility of waste minimization practices such as reusing and recycling of construction waste materials can be determined by performing a Cost-Benefit Analysis (CBA). From a case study conducted on commercial building project, Begum *et al.* (2006) reported that around 73% of waste materials (includes excavated soil) are reusable and recyclable. The authors pointed-out that CBA is important for the implementation of waste management systems in the construction industry in order to identify the economic benefits, including direct, indirect and intangible benefits due to the reusing and recycling of waste materials and its associated costs.

Begum *et al.* (2009a) conducted further study regarding insights on how contractors' attitudes and behaviors affect waste management practice in Malaysian construction sector and reported that contractors' attitudes towards waste management tends to differ based on the class of contractors or size of project. Larger contractors tend to have positive attitudes and satisfactory behavior toward waste management practices. The authors also found that about half of respondents (among 113 contractors surveyed) showed positive attitudes towards 3R practices which tend to show more satisfactory behavior toward waste management. Begum *et al.* (2009a) summarized significant factors which affect contractors' attitude and behavior toward waste management as shown in Table 2.8.

Table 2.8 Factors Affecting Contractors Attitudes and Behaviors (Begum *et al.*, 2009a)

Factors Affecting Contractors' Attitude	Factors Affecting Contractors' Behavior
contractor size	construction-related education level among employees
3R measures	contractors' experience
frequency of waste collection	source reduction measures
training program	reuse of materials
waste disposal method	waste disposal behaviors
	attitudes toward waste management

2.7.3 IBS in Malaysia

IBS existed in Malaysia since 1960s (Lim, 2006) where CIDB has been promoting IBS in Malaysia since 1998 to effectively coordinate construction sector towards industrialization (Haron *et al.*, 2009). However, Malaysian contractors still prefer employing conventional method over IBS (Mokhtar and Mahmood, 2008), mainly due to: lower cost; design flexibility; limited number of precast manufacturers and specialized contractors (Haron *et al.*, 2005). Nevertheless, there has been greater extent of IBS utilization over the past years and CIDB has established a dedicated IBS Center to provide information and resources related to IBS (CIDB, 2010; IBS Center, 2009).

2.7.3.1 Building Classification System

In 1998, Badir *et al.* introduced the Badir-Razali Building Classification System for building systems commonly exist in Malaysia according to method of construction (Figure 2.5). Based on Badir-Razali Building Classification, the 'cast in-situ', 'full prefabricated', and 'composite' can be classified as IBS.

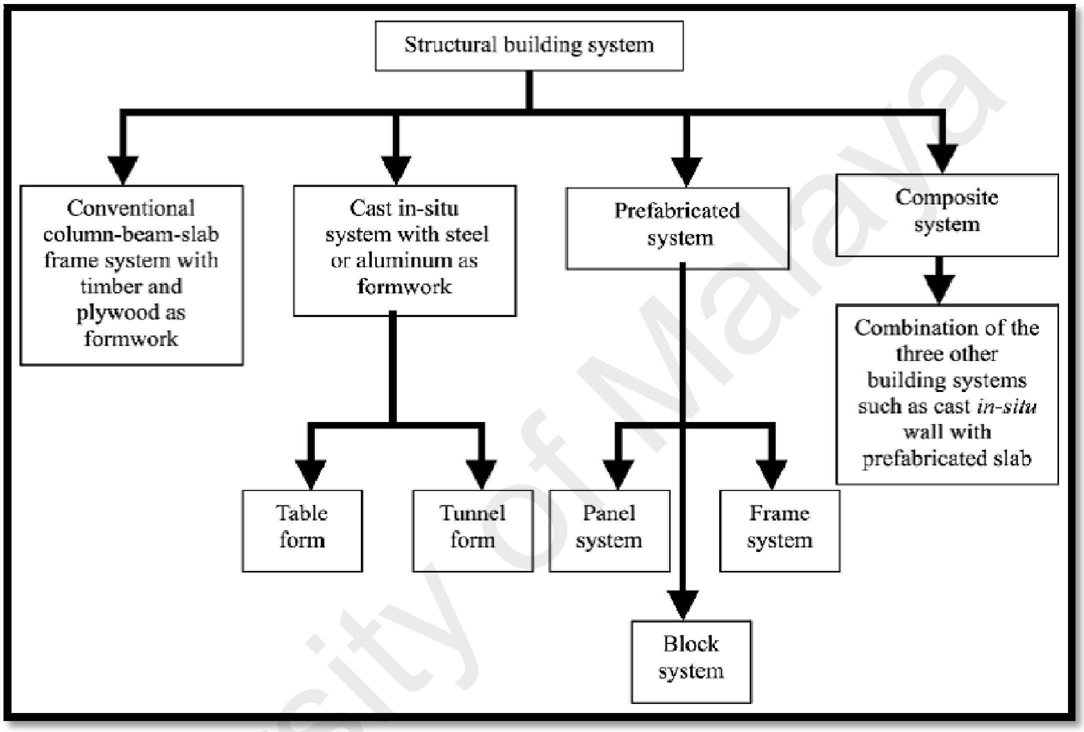


Figure 2.5 Badir-Razali Building Classification System (Source: Badir et al., 1998)

According to Haron *et al.* (2005), conventional method is mainly consists of timber formworks, steel reinforcement, and cast in-situ concreting (mostly reinforced concrete frame), while 'cast in-situ' method relies on the use of mould formwork and/or lightweight formwork (steel/aluminum). 'Cast in-situ' is suitable for country where unskilled labors are limited, whereby it eliminates or reduces traditional trades and labor content. Composite method is partially prefabricated, in which the objectives are to improve quality, reduce cost and completion time. Full prefabricated method entails that all elements are standardized and manufactured which can significantly reduce site labor and increase productivity. Badir *et al.* (2002) found that 45% of IBS systems employed in Malaysia are formwork system (fall under 'cast in-situ' method) with modular form being the most used type of IBS (32%), while precast load bearing wall panel system is the second most used system (21%). The authors added that off-site precast is more widely and popularly used in Malaysia.

2.7.3.2 Hindrances for Implementing IBS in Malaysia

Haron *et al.* (2005) carried out a comparison study between construction with conventional and formwork system and concluded that conventional method still costs less in Malaysia. The authors pointed-out that prefabrication is not flexible, in terms of negotiating for tender and selecting materials. Thus, it is no surprise that the level of IBS usage in Malaysia is only 15% in 2003 (Lim, 2006). Lim (2006) added that IBS works only when construction process requires speed, accuracy, and repetition work.

2.8 Overview on Conventional Construction Method

A brief overview on conventional construction is extracted from *Construction Methods and Management* by Nunnally (2007). According to Nunnally (2007), concrete construction is the most popular construction practice. Concrete is one of the world's most versatile and widely used construction materials, ranging from its use for foundation, through structural components such as beams, columns, and wall panels. Concrete components comprises of: cement, aggregates, water, and additives.

Structural concrete has traditionally been built in-situ by placing wet concrete into forms and allowing it to harden. The forms are then removed after the concrete has developed sufficient strength to support its own weight and loads. Typical shapes of concrete include walls, columns, beams, and slabs. Due to its small tensile strength, virtually all concretes used for structural purposes contain reinforcing materials embedded in the concretes to increase their tensile strength. Such concrete is called reinforced concrete. Steel reinforcing (rebar) is the most commonly used.

Major elements of concrete construction cost consist of: (1) formwork costs (including labor, equipment, and materials); (2) cost of reinforcing steel and its placement; (3) concrete materials, equipment, and materials.

Formworks for in-situ concreting is a mould or box into which wet concrete can be poured and compacted so that it will flow and finally set to the inner profile of the box or mould. Formworks also act as a temporary structure that supports its own weight and loads. Among the materials that can be used for formwork are timber, steel, and glass reinforced plastic. Timber is the most popular material for formwork because it is flexible, light weight, and easy to handle, but generate huge amount of timber waste as shown in Figure 2.6.

Figure 2.6 Timber Formwork in Cast-in-Situ Concreting

Since formwork may account up to 60 % of the cost of concrete construction, it is essential that the formwork plan shall be carefully developed and evaluated. Lower formwork cost will result from repetitive use of forms. Multiple-use forms may be either standard commercial (prefabricated formwork system) or custom-made by contractors (Figure 2.7). Finishing is the process of bringing the surface of concrete to its final position and imparting the desired surface texture. After structural, the next phase of construction process is internal finishing which comprises of mainly wet trade activities such as plastering, tiling, painting, cladding, etc.

Figure 2.7 Prefabricated Formwork System (Source: Poon et al., 2001b)

2.9 IBS Construction Method

2.9.1 Overview of IBS

Construction industry had been relying heavily on conventional method which typically employs timber formwork, in-situ casting and concreting, wet trades, and bamboo scaffolding. Poon *et al.* (2001b) described construction industry as labor-intensive, and polluting. Timber formwork, finishing wet trades, and concreting operations have been identified as the major contributors of construction waste. Low waste building technology utilizes prefabrication or IBS method which minimizes or even eliminates cast in-situ concreting, timber formwork, and wet trade activities, which contribute significant amount of waste.

2.9.2 Definition and Characteristics of IBS

Prefabrication or IBS method is defined as building elements which are manufactured at the factory or on-site prior to erection on building foundation. IBS is recognized as the solution for minimizing construction waste generation, whereby metal panel formwork, precast concrete elements and/or other manufactured building components are utilized instead of conventional temporary timber formwork, in-situ concreting, and wet trades which generate large amount of waste (Poon *et al.*, 2001b). According to CIDB (2010), IBS is also known as the complete assembly construction, which is a construction system where components are manufactured at factories or off-site, transported and then assembled into a structure with minimum work. Elements of IBS components comprise of: precast concrete elements (precast columns, precast beam, semi-precast slabs, facades, staircases, precast cladding); large panel formwork; alternatives formwork materials (aluminum, plastic or steel); precast drywall; precast bathroom and kitchen set, etc. Figure 2.8 – 2.10 present the installation of panel formworks, precast concrete, and manufacturing process of precast element.

Figure 2.8 Metal Formwork Systems for Slabs (Source: PERI)

Figure 2.9 Assembly of Precast Concrete Facades (Source: Poon et al., 2001b)

Figure 2.10 Manufacturing of Semi-Precast Slabs (Source: Poon et al., 2001b)

A survey conducted by Tam *et al.* (2007a) regarding respondents' view on prefabrication characteristics found that 'standardization', and 'design repetition' rank first and second, respectively.

2.9.3 Comparison between IBS with Conventional Method

As discussed earlier, the majority of waste is generated during concreting and wet trades activities, which contribute to about 80% of construction waste generated (Baldwin *et al.*, 2009). Baldwin *et al.* (2009) pointed-out that waste from direct or permanent work comprises of steel from reinforcement bars and spilled concrete, while waste from temporary work usually comprises of timber from formwork and scaffolding.

Similarly, Tam *et al.* (2007b) reported that huge waste reduction can be achieved for key activities such as concreting, plastering, and tiling by employing prefabrication instead of conventional method, as shown in Table 2.9. According to Poon *et al.* (2003), prefabrication generally offers more advantages than conventional system as shown in Table 2.10.

Table 2.9 Wastage between Cast in Situ and Prefabrication
(Source: Tam *et al.*, 2007b)

Trades	**Average wastage level (in %)**		**Percentage of waste reduction (C=(A-B)/A) (%)**
	Conventional (A)	Prefabrication (B)	
Concreting	20	2	90
Rebar Fixing	25	2	92
Bricklaying	15	-	-
Drywall	-	5	-
Plastering	23	0	100
Screeding	25	-	-
Tiling	27	7	74

Table 2.10 Comparison of Relative Advantages between Prefabrication and Conventional Method (Source: Poon *et al.*, 2003)

Building Conditions	**Advantage of:**	
	Prefabrication Construction Method	Conventional Construction Method
General market conditions		
High volume demand for buildings	V	
High construction wages	V	
Lack of skilled workers	V	
General project conditions		
Large and repetitive project	V	
High quality of work required	V	
Architectural features of the project		
High modularity of dimensions	V	
Special non-regular shape of the building		V
Special performance needs of the building		V
Special aesthetic requirements from components		V

Poon and Yip (2005) also concluded that selection of semi-prefabricated formwork system and materials for the construction of superstructures would seriously influence the cost, time, quality, and waste generation of the project delivery. Conventional timber formwork system is still more economically favorable in projects studied but resulted in very high timber consumption. If recyclable metal formwork used in the new system could be used, economic advantage would be realized as Poon and Yip (2005) reported that large panel formwork can be used by up to 100 times.

2.9.4 Benefits and Disadvantages of IBS

Studies (Baldwin *et al.*, 2009; De Silva, 2008; Tam *et al.*, 2002, 2007a, 2007b, 2008, 2009; Poon *et al.*, 2003, 2009; Poon and Jaillon, 2009) have reported that prefabrication/IBS significantly contribute to waste reduction. Haron *et al.* (2009) summarized the advantages of IBS which include: enhanced efficiency and productivity; better quality; reduce waste; higher quality of components; faster completion; and not affected by weather. Kadir *et al.* (2006) stated that IBS method performs better in terms of productivity, crew size, and cycle time. One of the most well-known characteristics of IBS is standardization, as previously reported by Tam *et al.* (2007a).Standardization increases buildability, construction speed, and utilization of reusable metal formwork for casting as repetition element is essential to meet the quantity for cost effectiveness (Poon and Jaillon, 2009).

In addition, Tam *et al.* (2007a) also found that prefabrication also improves construction safety by providing cleaner and tidier environment, thus increasing quality, productivity, and eliminating malpractices. Kadir *et al.* (2006) also concluded that IBS cut down labor usage, which leads to reduction of safety-related incidents, thus, it can lead to improved HSE (Health, Safety, Environment) performance and general site management, which are one of the main parameters for productivity.

A survey conducted by Poon *et al.* (2003) regarding the effects of using prefabrication concludes that, applying prefabrication improves works quality, reduces wastage and completion period, but it is cost-intensive and less flexible. While according to Tam *et al.* (2007b), the main advantage of applying prefabrication is ‘better supervision’, which means better quality control. As an illustration, a case study conducted by Tam *et al.* (2009) revealed that installing precast concrete slabs can avoid excessive waste (mainly concrete) produced by up to 71% due to construction of temporary works. When design changes and uncertainty happens, temporary works need to be done repeatedly for several times. Tam *et al.* (2009) reported that precast slabs can be used repeatedly up to five times.

On the other hand, Poon *et al.* (2003) cited the drawback of prefabrication which include: (1) low revenue for small projects; (2) low flexibility in design variation; (3) not allowed to change layout; and (4) feasibility must take account economic, situation, and architectural features which are not common for private projects. Tam *et al.* (2007b) found that the main difficulties in applying prefabrication are ‘inflexibility’, and ‘lack of information’ (Figure 2.11).

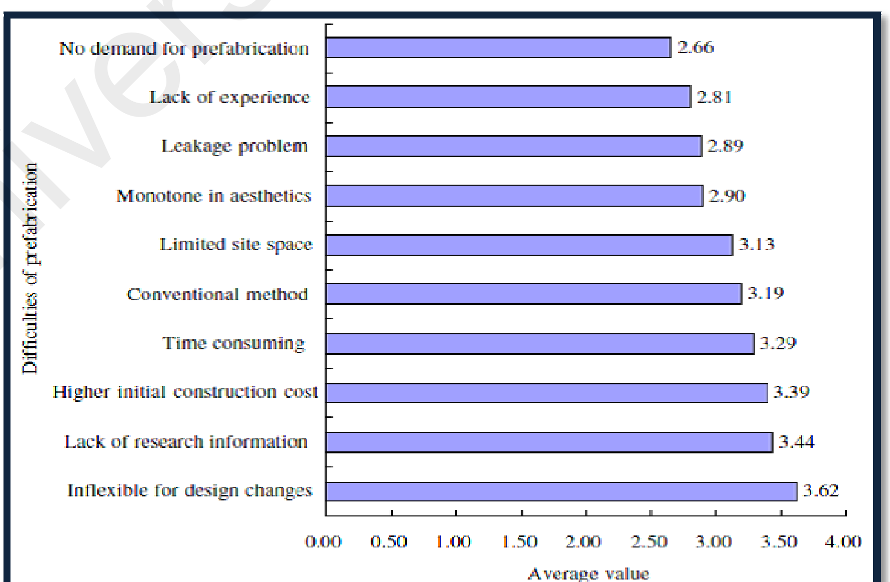


Figure 2.11 Hindrances to Applying Prefabrication (Source: Tam et al., 2007b)

Meanwhile, Baldwin *et al.* (2009) listed-out the disadvantages of precast construction, such as: (1) longer time in design and approval; (2) higher initial cost; (3) quality control and procurement problem if manufactured abroad; and (4) storage and protection. The aforementioned concluded that the cost of adopting prefabrication may be higher due to: setting up fabrication yard; transportation; labor training; and jointing problems. Thus, it is no surprise that the market for prefabrication is dominated by leading contractors. Even though IBS has been mandatory and continuously used for public housing projects in Hong Kong, but for the higher extent of adoption, there has to be more demand from clients, especially from private sector (Chiang *et al.*, 2006).

In addition, adoption of low waste building technologies is constrained by a number of factors. Poon *et al.* (2003) reported that most contractors were not aware of the importance of waste minimization. 'Cost' and 'time' were considered as their primary concerns for decision-making of construction method, while waste reduction is considered the least important concern. Meanwhile, Zhang *et al.* (2012) reported that 'high costs' and 'insufficient government support' as the main challenges in implementing low waste building technologies.

2.10 Previous Studies on Construction Waste Quantification

Waste characterization is the initial stage of data gathering and it is very crucial. The process consists of identifying type of waste materials being generated. Recent development in construction waste quantification methods from literatures are presented below. The scope of these methods are applicable only for building construction projects and not include civil/infrastructure, demolition, and renovation projects.

1. *Method Suggested by Gavilan & Bernold (1994), and Bossink & Brouers (1996)*

These authors can be considered as the pioneer who developed the early waste source and waste quantification model. Gavilan and Bernold (1994) addressed the critical steps in developing comprehensive waste management system which are: categorization and quantification of construction waste generation, thus, prompted the development of framework for waste source model. According to Gavilan and Bernold (1994), waste quantification model can be defined as waste generation-rate model. Source identification of construction waste generation includes: design; procurement; handling; operation; and residual. Bossink and Brouers (1996) were among the first to estimate the amount of wastage materials of waste generation in Dutch construction industry. It is approximated that 1 to 10% of materials ordered would end up as waste and most waste came from leftover cut-off, design changes, and poor workmanships. Thus, it can be concluded that reducing waste at the source is the most important target in waste management as it demonstrates productivity of a project.

2. *Method Suggested by Poon et al. (2001b, 2004, 2009)*

As mentioned earlier in previous section, Poon *et al.* (2001b) introduced the 'waste index' approach, which is defined as the amount (in unit of volume or weight) of construction waste generated per m^2 of Gross Floor Area (GFA hereafter) or area of activity. Waste index calculations can anticipate the quantity of waste that may arise in order to establish awareness of waste minimization, to develop good planning on resources and environmental management and to reduce the wastes generated during all stages of a construction project (Poon *et al.*, 2004). This is an excellent and proven means to assess and standardize baseline value for the environmental performance of construction project and has been widely implemented on building projects, especially public housing in Hong Kong (Poon *et al.*, 2004 & 2009). The method for calculating waste index and total generated waste may be described as follows:

(W) = Total waste generated by the project (m^3/tonnes)

(C) = Waste index = (W)/m^2 GFA (1)

i.e. 1 m^2 area of GFA generates (C) m^3 of waste

[Total waste generated by a project] = [GFA of the project] x [waste index] (2)

Based on waste generation per GFA, it has been found that the generation rate of construction waste was in the range of 0.125 m^3 to 0.25 m^3 (waste index) per gross floor area GFA (m^2). As a rule of thumb, contractors use the following standard figures in Hong Kong's construction industry as given in Table 2.11.

Table 2.11 Waste Index for Various Types of Project in Hong Kong (Source: Poon *et al.*, 2001b)

Project	Waste Index
Public residential	0.175 m^3/m^2 GFA
Private residential	0.250 m^3/m^2 GFA
Commercial office	0.200 m^3/m^2 GFA

However, waste index only represents general estimation. The actual composition of construction waste on site could not be identified unless further waste audit and sampling were conducted. Thus, the term 'wastage level' was also introduced by Poon *et al.* (2001b) to approximate the 'theoretical' composition of various construction materials that are likely to end up as waste by accounting the quantity of materials being used/done and the actual quantity of materials ordered, which is based on extensive surveys. Table 2.12 presents the findings for various material wastages for public residential projects in Hong Kong.

Table 2.12 Material Wastage Levels for Public Residential Projects in Hong Kong

(Source: Poon *et al.*, 2001b)

Trade	Material	Percentage Wastage
Concrete	Concrete	3-5%
Formwork	Timber broad	5%
Reinforcement	Steel bars	3-5%
Masonry	Brick and block	6%
Dry Wall	Fine aggregate	5%
Wall Screeding	Ready-mix cement	7%
Ceiling Screeding	Ready-mix cement	1%
Wall Plastering	Plaster	2%
Ceiling Plastering	Plaster	2%
Floor tiling	Tiles	6%
Wall tiling	Tiles	8%
Installation of bathroom fitting	Sanitary fitting	2%
Installation of kitchen joinery	Kitchen Joinery	1%

Wastage level should be compared with the norm, i.e. the average performance of the industry. More importantly, material and waste audits should be carried out in order to identify area (sources and causes) that could be improved in subsequent projects. It has been found that the average quantity of waste per GFA was about 0.3 tonnes/m^2 for conventional projects and 0.14 tonnes/m^2 for prefabricated buildings (Poon *et al*., 2009). Poon *et al.* (2009) concluded that the amount and type of C&D waste depends on: type of projects (i.e residential or commercial); size of the projects; and construction technology employed.

3. *Method Suggested by Jalali, S. (2006)*

Method suggested by Jalali (2006) pointed out the significance of project analysis in terms of rough waste estimation prior to undergoing a building project in Portuguese construction industry. 'Wastage Level' concept which is based on database from previous project is proven to be useful to provide rough waste estimation. Detailed construction work schedule could be regarded as an essential tool to provide likely timetable for waste generation. Jalali (2006) implemented ‘Global Index ‘and ‘Component Index’ approaches for quantifying construction waste generation for building construction projects in Portugal. ‘Global Index’ provides the necessary indicator for given type of building which can be used for similar future projects and facilitate the overall estimation of waste in unit amount/area of activity (GFA). This approach can also be utilized for quantification of regional or even national level construction waste generation.

‘Component Index’ approach provides quantification of each construction component that composes the overall projects, such as timber, concrete, reinforcement steel, tiles/ceramic, and packaging. Each construction component (CC) employs its own unit of measurement, which depends on the material (e.g.: 1 m^2 of tiles). There are 30 Construction Components elaborated by Jalali (2006) in establishing reliable database for Portuguese building construction industry. Component Index is heavily depending on the use of detailed spreadsheet that list-outs construction component and their amounts in specific units. ‘Global Index’ approach measures total waste produced on site. It is presented in a simple spreadsheet that accommodates waste index at different units (volume/GFA, weight/GFA, volume/cost, and weight/cost) for each waste component as illustrated in Table 2.13.

‘Global Index’ can be considered as the summary ‘Component Index’ spreadsheet and it is similar to Poon’s ‘Waste Index’ approach. Global and Component Index are considered to be more detailed, resourceful, and specific than Poon’s waste index but there is some likelihood to be confusing in terms of difficulties in implementation due to rather complicated component index spreadsheet, especially in utilization of different unit of measurement for different components. It is noteworthy that there is a need to update and refine empirically gathered data progressively from time to time in order to increase the data accuracy, which consequently increases the applicability of this approaches.

Table 2.13 Management Indicator For a Given Building (Source: Jalali, 2006)

Core numbers	Waste amount m³/m³ gross volumn	Waste amount m³ / m² gross floor area	Waste amount m³/ 1000 Euro construction costs	Waste amount t /m³ gross volumn	Waste amount t / m² gross floor area	Waste amount t / 1000 Euro construction costs
Wood	0,00146	0,00438	0,00875	0,00022	0,00066	0,00131
Foil	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000
Metal	0,00061	0,00184	0,00368	0,00012	0,00037	0,00074
Concrete	0,00178	0,00535	0,01070	0,00004	0,00011	0,00021
Mixed Construction Waste	0,31874	0,36923	0,73845	0,00197	0,00591	0,01182

Construction Waste Management

Used containers	Type and size	waste type	duration in months	number of containers	containter costs in Euro/month	transportation costs in Euro/transport	disposal price in Euro/t
Waste bags	Plastic bags 0,25 m3	light wastes	12	40			30
Waste containers	Plastic containers 0,25 m3	heavy wastes	12	5			30

4. *Method Suggested by Lau et al. (2008)*

Lau *et al.* (2008) highlighted the importance of waste sampling to categorize and estimate construction waste generation by conducting case study for waste quantification and classification in five housing projects in Sarawak. Lau *et al.* (2008) employed a unique method in quantifying layout of construction waste on site. The layouts of construction waste generated on site were divided into four forms: stockpiled, gathered, scattered, and stacked. Quantities of waste generated, in terms of weight, for a particular layout were determined through the product of its respective estimated volume and estimated unit weight.

For example, for stockpiled waste, it was assumed to stay in the form of rectangular base pyramid-shaped (Figure 2.13) which can be quantified by simply calculating the volume of pyramid-shaped stockpiled waste, whereby: Vs = 1/3 (B x L x H). Whereby gathered waste, it was assumed to stay in the form of rectangular prism on the ground surface (Figure 2.14). The volume of gathered waste would be Vs = L x B x

H. For scattered waste with similar size, three samples were randomly chosen and weighed. The values obtained were averaged and assumed to be the same for all other samples. Subsequently, the number of samples scattered around the site were counted and recorded. The average weight per sample multiplied by the number of samples gives the total weight of the scattered waste. For stacked waste, it was measured in a similar manner as scattered waste. The results for waste quantification for each waste component are presented in 'tonnes per hectare of sites'. Timber made up the most of construction waste in all sites, followed by concrete waste.

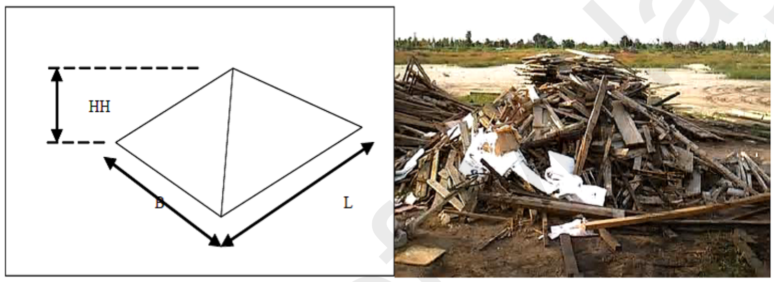


Figure 2.5 Stockpiled Waste (Source: Lau et al., 2008)

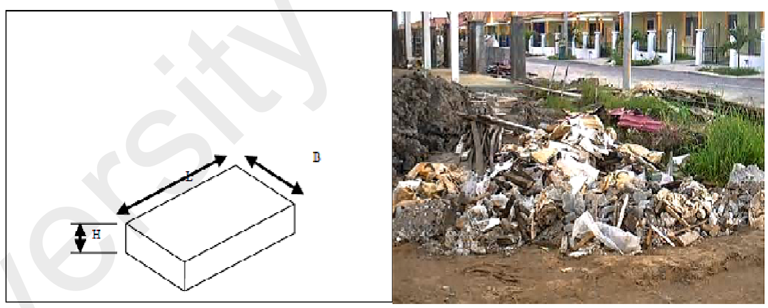


Figure 2.6 Gathered Waste (Source: Lau *et al.*, 2008)

5. *Method Suggested by Soliz-Guzman (2009)*

Solis-Guzman *et al.* (2009) developed the method to quantify various waste materials with detailed classification system. The fixed waste factors were based on rigorous surveys from numerous project sites in Spain and also supported by strong Andalusian database for Spain's construction industry. The database provides relatively accurate quantified and standardized information, which means better waste characterization and thus, a strong set of data. The author described the waste minimization model that has inspired the decree (Alcores model) and has been implemented with good result in Seville, Spain. The model provides the volume estimation of building-related waste. The models to estimate the volume of building-related construction and demolition activities, respectively, which expressed as follow:

$$Q= (VAR + VAE, [m^3/m^2]) \times (GFA, m^2) \quad (3)$$

$$Q= (VAD, [m^3/m^2]) \times (GFA, m^2) \quad (4)$$

- *VAC=VAC=Q_i(quantity, x/m^2) x CC_i(conversion ratio, m^3/x) → apparent constructed volume/GFA*
- *VAD=VAC x CTi → apparent demolished volume*
- *VAR=VAC x CR → apparent wreckage waste volume*
- *VAE=VAC x CE → apparent packaging waste volume*
- *CTi,CR,CE: dimensionless coefficients*

The term (*VAD* or the sum of *VAR + VAE*) is similar to 'waste index' concept (Poon *et al.*, 2001b) as waste generation factor in the quantification model. Both models quantify the waste by volume (m^3).

6. *Model suggested by Llatas (2011)*

This quantification model serves as a continuation from the model proposed by Solis-Guzman *et al.* (2009) to support the recent EU directive to become a "recycling society" as the new challenge is to recover 70% by weight of C&D waste by 2010. Llatas (2011) utilizes very systematical approaches by: identifying building elements of the project and their construction processes; employing waste classification system (including remains, soil, and packaging); and modeling (Figure 2.15). The analytical expressions used are the following:

$$CW_B = \sum_j CW_{SBEj} = \sum_{ji} CW_{BEi}$$

$$= \sum_{ji} CW_{Pi} + \sum CW_{Ri} + \sum_{ji} CW_{Si} \quad (5)$$

CW_B = Volume of waste expected; CW_{SBEj} = Volume of waste expected in the system building element "j"; CW_{BEi} = Volume of expected waste from building element "i"; CW_{Pi} = Volume of expected packaging waste element "I"; $\sum CW_{Ri}$ = Volume of remains expected from building element "i"; CW_{Si} Volume of expected soil in building element "i".

$$CW_{Pi} = \sum_k (EWL)_{pk}.Q_i.F_P.F_C.F_I \quad (6)$$

$$CW_{Ri} = \sum_k (EWL)_{Rk}.Q_i.F_R.F_C.F_I \quad (7)$$

$$CW_{Si} = \sum_k (EWL)_{Sk}.Q_i.F_S.F_C.F_I \quad (8)$$

$(EWL)_{pk}$ = Code of packaging; $(EWL)_{Rk}$ = Code of remains $(EWL)_{Sk}$ = Code of soil; Qi = Amount of building element "i"; F_P = Packaging waste factor; F_C = Conversion factor; F_R =Remains factor; F_S = Soil factor; F_I = Increased volume factor

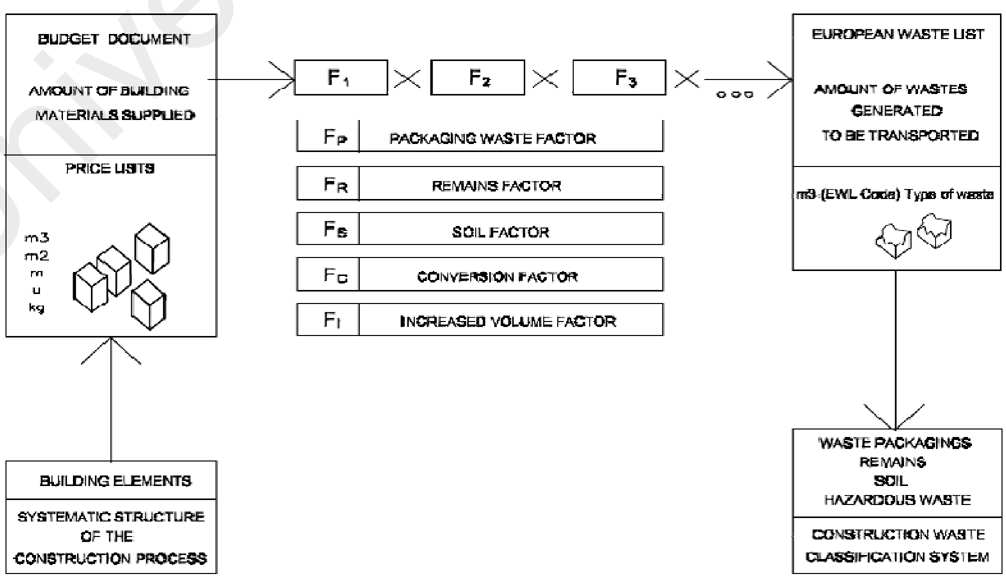


Figure 2.7 Basic Tool of the Model (Source: Llatas, 2011)

Based on case study for a number of dwelling projects in Spain involving over 200 building elements in a single project, waste generation rate (without soil) of 0.1388 m^3/m^2 was obtained. A rate of packaging waste generation of 0.0819 m^3/m^2 and a rate of 0.0568 m^3/m^2, and soil generation of 0.2805 m^3/m^2 were obtained. With this model, chances for construction waste recovery and prevention could be increased.

7. *Method Suggested by Building Research Establishment (BRE), UK*

The Resources Efficiency team at BRE has developed a measurement tool which is known as the SMARTWaste System in order to help contactors in improving their waste management strategy. The system is entirely web-based and enables immediate and automated reporting and includes two waste auditing tools (SMARTStart™ and SMARTAudit™) which can be found at *http://www.smartwaste.co.uk*. **SMARTStart**™ is a software tool enabling the user to define their environmental and key performance indicators (EPIs and KPIs) for waste generation on a site by site, and organization basis. While **SMARTAudit**™ is a tool to quantify major waste components generated on site from the processes causing it to what it costs, identify waste and target it at source to reduce it and maximize recycling potential. SMARTAudit requires good record-keeping and waste accounting to collect reliable and accurate data. Data from the tool system have been used to develop performance indicators. The performance indicators are based on actual volumes for completed new build projects. The results from this tool will generate detailed spreadsheets, reports, charts, and performance information (Figure 2.16). The following indicators are currently measured and updated monthly:

- Average m^3 of waste /100m^2 of floor area for different project types. This is similar to waste index.

- Average m^3 of waste/£100,000 of project value for different project types

On the whole, these waste minimization tools are considered simple, user-friendly, reliable, and readily accessible.

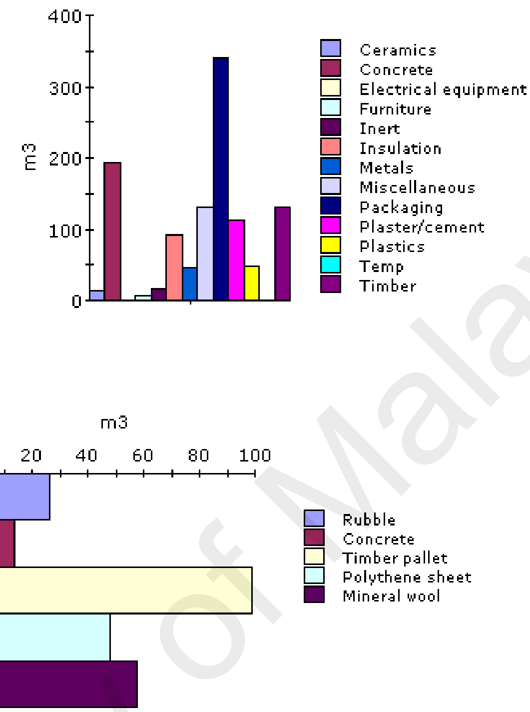


Figure 2.8 Charts Generated By SmartAudit Tool

8. *Method Suggested by Katz and Baum (2011)*

One of the most recent study conducted by Katz and Baum (2011) reported a novel approach in waste modeling whereby waste accumulates in an exponential manner, i.e. significant amount will likely to be produced towards the end of a project. The authors conducted surveys on 10 new multi-storey residential sites in Israel. Site observations were carried out to evaluate composition of waste, and to estimate the construction stage at a given time. Total accumulated waste was recorded periodically as construction progresses. Construction processes were divided into three phases, structural works; early finishing; and late finishing works. Since monitoring waste generated on a project until its completion is unpractical, empirical model was developed in order to produce a tool to estimate the amount of waste generated on a construction project. The derivative of this equation yields the rate of waste accumulation at each stage of the construction works, whereas integration over a certain period or over the entire project lifetime (Eq. (9) yields the waste accumulated during this period or the total waste, V_{tot}, generated on the site, respectively:

$$V = \int_{\tau 1}^{\tau 2} \varphi(\tau) d\tau \qquad (9)$$

The function was determined experimentally according to the field survey described above. The monthly quantities of waste measured on each construction site were converted to *V(i)* using:

$$Vn(i) = \frac{V(i)}{A} D \qquad (10)$$

Where *Vn(i)* is normalized amount of waste as measured by the *i-th* monthly sampling, expressed in m^3 per 1 m^2 floor area. *V(i)* is absolute monthly amount of waste as measured by the *i-th* monthly sampling, m^3. A is total built area of the project, m^2. *D* is the total duration of the project, months. The normalized time of each sampling is calculated according to:

$$\tau(i) = \frac{m(i)}{D} \qquad (11)$$

Where τ *(i)* is normalized time of the *i-th* monthly sampling. *m(i)* is month in which the *i-th* monthly sampling was taken. *D* is the total duration of the project, months. Integration of the regression line enables to predict the amount of waste generated during various stages of the construction life (Eq. (9)), as shown in Figure 2.17.

It was found that total amount of waste expected from typical high-rise residential project is estimated and validated around 0.2 m^3/m^2. From the figure, it can be seen that during the first third of project's duration most of the works are related to structural and may generate around 5% of the project's total waste. At this early phase, waste is characterized by recyclable materials such as concrete, blocks, and rebars. The final third's duration produces 65% of the entire project's total waste. Hence, recyclables decrease due to increased packaging materials.

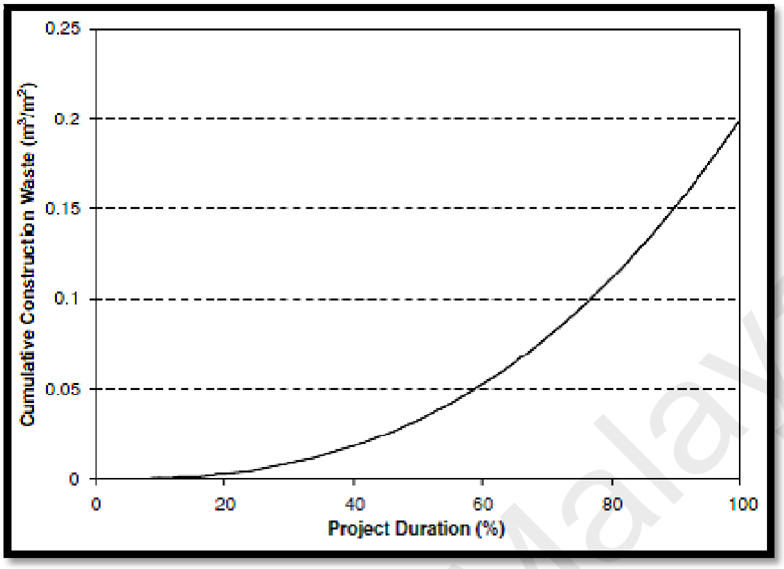


Figure 2.9 Typical Accumulation of Construction Waste throughout Total Project Duration (Source: Katz and Baum, 2011)

2.10.1 Summary of Waste Quantification Methods

Poon's method in calculating waste index is considered to be the benchmark of waste estimation method in building projects. This is an excellent and proven means to assess and standardize baseline value for the environmental performance. Wastage level approach is also excellent for estimating quantity of individual construction materials that are likely to end up as waste based on common material accounting. Poon's method is the only one that relates waste estimation with construction method employed (i.e. prefabrication and conventional).

Most of the newer quantification methods are basically improvement and customization of Poon's waste index. Jalali's Global Index (GI) is regarded to be very resourceful as it produces waste index in a variety of terms, such as 'weight/GFA', 'weight/construction cost', 'volume/GFA', and 'volume/cost'. Construction Components (CC) spreadsheet is believed to be quite complicated in terms of ease of implementation in record-keeping due to usage of different unit of measurement for each waste component. However, CC spreadsheet lists out a complete database of considered construction materials.

Method proposed by Soliz-Guzman (2009) for Spain's construction industry is another case of detailed spreadsheet which is supported by strong Andalusian database of construction components acquired from rigorous waste assessment on project sites, but complicated calculation and usage of a variety of unit measurement stand in the way of user-friendliness in record-keeping. While quantification models proposed by Llatas (2011) provide a reliable and detailed approach for estimating waste generated from an individual construction project, taking account of soil, remaining (wrecked) materials, packaging, and even hazardous waste to comply with stringent EU requirements.

Lau's method in quantifying construction waste seems to be inaccurate due to over-simplified estimation, lack of strong database due to limited number of sampled sites, and lack of resourceful information presented. However, Lau's method is quite easy to carry-out and can provide rough estimation with little effort and time.

SMARTAudit provides an innovative and user-friendly web-based waste auditing tool. One can conduct scheduled record-keeping and quantify waste effortlessly. However, user should be weary of the construction waste database accuracy and comprehensiveness as it needs to be refined and improved from time to time. Meanwhile, novel approach in waste modeling whereby it is found that waste accumulates in an exponential manner as reported by Katz and Baum (2011) is quite interesting. This would be a good addition to existing and established quantification methods for phase-bound waste estimating. This is in fact correlated with study as reported by Tam *et al.* (2007b) which stated that most of the waste is generated from finishing/wet trades. However, more studies and implementations need to be done for this relatively new quantification method.

It is believed that some combination of these quantification methods would make a good impact in accurate numerical estimation of construction waste amount generated in building construction projects. It is noteworthy that construction waste database must be refined, improved, and updated regularly. Poon's waste index and wastage level are reliable and versatile for industry application. This is very suitable for implementation in developing country like Malaysia. Advanced methods proposed by Jalali (2006), Soliz-Guzman *et al.* (2009) and Llatas (2011) require established national database and detailed standardization which require stringent enforcement from authorities. These methods would be time/resources-consuming and very difficult to implement in developing country like Malaysia, whereby there are lack of established waste database and standardization among industry players and associated stakeholders.

2.11 Environmental Impacts Assessment in Construction Industry

Previous sub-chapters have described the impacts of construction industry to environment and the need to reduce waste generation and its associated impact to a more sustainable level. Therefore, it is important to quantify the environmental impacts of construction waste. Environmentalimpacts assessment involves the estimation and evaluation of risk to the environment caused by a particular activity or exposure (Burgess and Brennan, 2000). This activity or exposure may be linked to any part of a product life cycle, for example not only in the use or disposal of a product, but also from processing, transport and storage of materials during product manufacture and distribution. The impacts will be suffered by the environment and may be harmful to human.

Construction industry consumes large quantities of raw materials. The type of materials produced to serve the industry are ranging from raw goods such as sand, aggregates, soil and water to manufactured goods such as bricks, cement, plasterboard, metals (steel and iron), timber, concrete, and plaster. As a consequence of large consumption of these materials, waste is generated in large quantities, which can pose significant impacts on the environment. From the total of generated C&D waste stream in the US, 92% was attributed to demolition activities and the other 8% to construction activities (Kibert, 2002).

A recent study from EPA (2009) shows that construction is the third largest industry sector in terms of contributions to greenhouse gas emissions in the United States. As the country with the fastest development of infrastructures, China has spent one-sixth of the total energy in 2007 to buildings and infrastructures construction, in conjunction with the developments in industry and transportation (Chang *et al.*, 2010). Although carbon emissions generated is low, the construction phase portion of the total life cycle of a building releases significant amount of carbon emissions in a relatively short time horizon (Säynäjoki *et al.*, 2011).

Presently, several models and systems for assessing environmental impacts of buildings have been developed in China. However, most of the models, such as the Evaluation System for Eco-buildings in China (ESEB) and the Green Olympic Buildings Assessment System, were based on qualitative scoring methods. The scoring system was easy to use, but sometimes subjective, which makes it difficult to provide in-depth and comparable results (Li *et al.*, 2009).

2.11.1 Review on Life-Cycle Assessment (LCA)

The widely used method to assess the impact of construction activities on the environment is LCA. Life Cycle Assessment (LCA) is one of the most comprehensive and accurate tool for quantitative analysis of environmental impact over all life cycle stages of product s' life. Despite its usefulness, full LCA requires lengthy time span as well as financial resources (Kim *et al.*, 2005). These inherent issues make full LCA hardly able to be applied in industry. Simplification in conducting LCA, by reducing the complexity of product system boundary related to particular goal of LCA study, is one approach to spread the use of this tool (Lee *et al.*, 2004). Most of the time, comparison of a number of different LCA studies is required. In this case, a single unit or impact indicator is often preferable.

Global warming is a major and eminent environmental issue and shall be emphasized in this study. Garcia *et al.* (2007) studied LCA of two different types of building material (natural stone and artificial stone). Results suggest that 90% of natural stone's total impact is to human respiratory organ due to inhalation of dust during production processes, while fossil fuels (energy depletion) is responsible for almost 50% ofartificial stone's total impact for generating electricity. Other study conducted by Trusty and Meil (2002) by comparing three types of building design: wood; concrete; and steel design. The authors reported that concrete-made building has the highest global warming potential, which is 93,573 kg of equivalent CO_2, while wood-based and steel-based building has 62,183 kg and 76,453 kg of equivalent $CO_2$for global warming potential, respectively.Some of previous studies had focused on comparing different LCA methods and their applicability in various conditions (Säynäjoki *et al.*, 2011).

Nowadays, ecological impacts tend to be dominated by economic argument whereby quantification of the costs of action against the costs of the consequences of inaction must at least be attempted (Houghton, 1997). Other than carbon footprint, another indicator, eco-costing which is one of the recent advances in LCA analysis, is gaining popularity. Eco-costs can be presented in the form of either 'prevention-oriented' costs or 'damage-oriented' costs, depending on how valuation of costs after the assessment of impact is made.The ecological cost includes the direct and indirect environmental costs of the construction process (Yahya and Boussabaine, 2006). Each activity in construction requires a large number of materials in many types, and these activities release impacts to environment, whether in the form of indirect or direct costs. The cost breakdown of eco-costs for construction waste during construction stage are the sum of eco-costs from emissions, eco-costs from energy, and eco-costs from resources depletion. Both carbon footprint and eco-cost will be reviewed in subsequent sections.

LCA is a methodology for evaluating the environmental impacts and energy consumption of processes or products during their life cycle. LCA can also be used to study which raw materials and energy types were used in producing products or providing services and to assess the environmental impact.

LCA is proposed to be a cradle-to-grave analysis and it can be divided into three phases: cradle to entry gate; entry gate to exit gate; and exit gate to grave. The cradle to entry gate phase starts from extraction of raw materials. It embraces all the processes for producing the construction materials and components required and bringing them to the site for constructing the building. The entry gate to exit gate phase corresponds to the construction phase of a building. During this phase, materials and energy are consumed and construction wastes generated. The construction phasereleases significant amount of carbon emissions in a relatively short time horizon (Säynäjoki *et al.*, 2011). Exit gate to grave includes all materials and energy consumed during in-use period, renovation, demolition, and waste disposal (Figure 2.18).

According to the Society for Environmental Toxicology and Chemistry (SETAC), LCA is typically divided into four steps: goal and scope definition, inventory analysis, impact analysis and interpretation (Figure 2.19). The first step is to define the scope of the study, including defining the functional unit, the system boundary, level of detail and how the environmental burdens will be allocated.

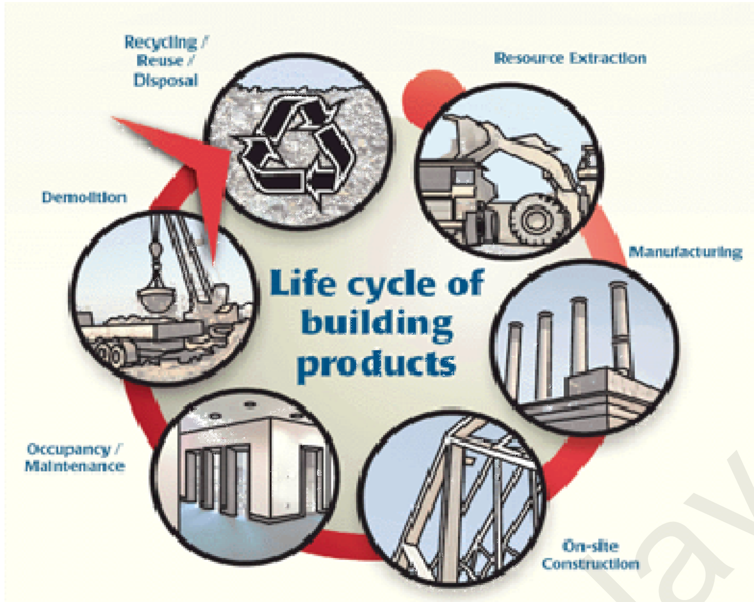


Figure 2.17 LCA of Building Products (Source: www.pci.org)

Inventory analysis, as stated in ISO14040 (2006), is a process that quantifies the input of a production system, such as energy, materials, and chemicals among others, and the output of the system that is released back into the environment, such as CO_2. There are three kinds of methods used to calculate the impact of construction process to environment, which are: process analysis; input-output analysis; and hybrid analysis. These types of methods determine the inventory database needed. Process analysis makes its inventory database by tracing production processes of each product. This method is the most complex than the other, but has the highest accuracy. Input-output analysis makes its inventory database by using material types and unit costs that were collected from bill of quantity (BOQ) of the project. Calculation ofCO_2 emisions by input-output analysis can be expressed in the following equation as proposed by ISO14040 (2006).

$$Amount\ of\ CO_2\ emissions = \Sigma(W_i \times C_i \times CO_i) \quad (22)$$

Where, Wi: amount of waste generated by each material, C_i: unit cost by each material and CO_i: unit amount of CO_2 emissions by each material.

The last method is hybrid analysis. This method is a combination of process analysis and input-output analysis.

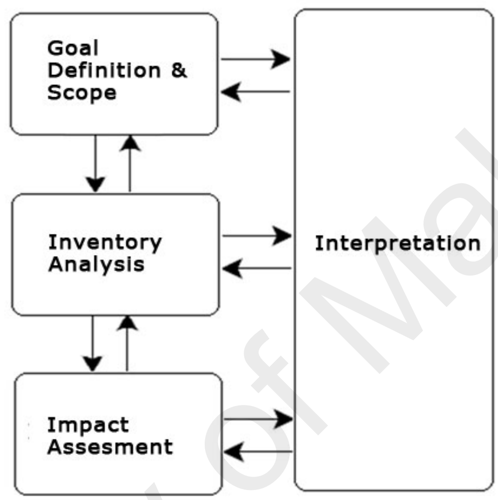


Figure 2.18 LCA Frameworks (Source: ISO14040, 2006)

Impact analysis can be divided into three sub-steps: classification; characterization; and valuation (weighting). Weighting is used to evaluate the relative severity of the impact categories to integrate different types of contributions into one single value. To determine whether an environmental aspect is significant, a four-interval scale of impacts severity was developed: non-existent impacts; non- significant impacts; marginally significant impacts; and extremely significant impacts. The results of an LCIA (or an LCI in a partial LCA study) are summarised to form a basis for conclusions, recommendations and decision making (ISO14040, 2006).

A LCA model relies on a life cycle inventory (LCI) database to provide data regarding the economic and environmental impact that will occur by consumption of materials and energy for construction, operation, and demolition of buildings. There are two databases of LCI mostly used for LCA research: Ecoinvent and Idemat which contain over 4500 LCIs, and 900 LCIs, respectively (Ecoinvent, 2010 and IDEMAT, 2010).

Ecoinvent are representative for European region, in this case, Switzerland. LCA database with data applicable to the Asia Pacific region had already begun to be established in 2000. Initial moves towards achieving this had been taken, driven largely by Japan. The Japan Environmental Management Association for Industry (JEMAI) launched a project with Korea, Chinese Taipei, Malaysia, and Thailand to exchange information and to develop LCI data in cooperation with these countries on energy and a few basic materials. But unfortunately LCI database for specific region such as Malaysia are basically still unavailable.

2.11.2 Carbon Footprint

The term "carbon footprint" has become widely used in recent years, associated closely with global climate change and environmental impact assessment, especially in global warming potential. There are several definitions of this term, as well as some difference in what it actually means and measure and what unit should be used (Wiedman and Minx, 2008). This term is defined as the total Greenhouse Gas (GHG hereafter) emission from our activities which is caused by an organization, party, and also by an individual (Wiedman and Minx, 2008). For convenience, it is regularly expressed as the amount of carbon dioxide or its equivalent of other GHGs and has units of tonnes (or kg) of carbon dioxide equivalent. Wiedman and Minx (2008) propose the definition of this term as a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the live stages of a product.

The carbon footprint of a building can be divided into two items, which are embodied carbon and operational carbon. Embodied carbon from building comes from the emission produced in production phase, their transport and assembly on site, maintenance and replacement, disassembly and decomposition, while operational carbon is produced when the building is in operation (Wiedman and Minx, 2008).

Carbon footprint has been established as the common way to examine GHG emissions related to certain processes or goods. There are a number of techniques in estimating carbon footprint. The first technique is to account only carbon dioxide emission. The second technique involves examining other emissions classified as GHGs equivalent to CO_2 (such as NOx and SOx) and does not include other (toxic) substances that might be harmful to the environment.Determination of carbon footprint is based on a life cycle assessment where climate change is the only effect group (Seppala *et al.*, 2009).

BIS (2010) carried out a study to estimate the amount of CO_2 emissions influenced by the construction industry. The calculation was done for the life cycle of the building can be seen on Figure 2.20, while the result is shown on Table 2.14.

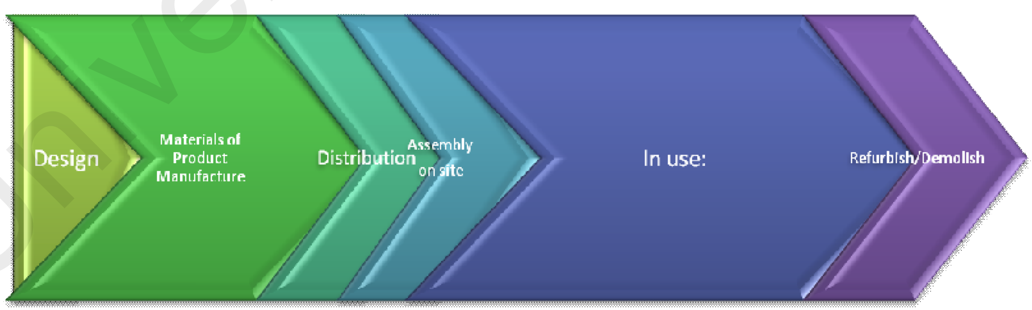


Figure 2.19 Building Life Cycles (Source: BIS, 2010)

From this result, it can be concluded that the largest portion of carbon emissions come from the operation phase (In Use), while the biggest contribution in construction phase is the manufacturing processes of construction products and materials.

Table 2.14 Amount of CO2 Emissions from Construction Industry (Source: BIS, 2010)

Sub-Sector	$MtCO^2$	% of total
Design	**1.3**	**0.5%**
Manufacture	**45.2**	**15%**
Distribution	**2.8**	**1%**
Operation on site	**2.6**	**1%**
In Use	**246.4**	**83%**
Refurb/Demolition	**1.3**	**0.4%**
Total	**298.4**	**100%**

Studies have shown that buildings with wooden structures require less energy and emit less CO_2 during their life cycle compared to buildings with other types of structures (Buchanan and Levine, 1999). Various life cycle studies which had been carried out indicate the advantages of wooden structures. The quantity of greenhouse gases emissions avoided by replacing steel with wood in buildings in Norway and Sweden was up to 0.88 kg CO_2-Eq/kg input of timber; while replacing concrete with wood reached up to 1.77 kg CO_2-Eq/kg (Petersen and Solberg, 2005). In general, all wood-based construction materials have a lowerimpact, especially specific products that require less industrial processing. Table 2.15presents LCA results for wood products (Zabalza-Bribián *et al*., 2011).

Table 2.15 LCA results for Wood Products (Source: Zabalza-Bribián *et al.*, 2011)

Building Product	Global Warming Potential(kg CO_2-Eq/kg)
Sawn timber, softwood, planed, kiln dried	0.300
Sawn timber, softwood, planed, air dried	0.267
Glued laminated timber, indoor use	0.541
Particle board, indoor use	0.035
Oriented strand board	0.620

2.11.3 Eco-Costing and Eco-Costs per Value Ratio (EVR)

Eco-cost is measure to express the amount of environmental burden of a product onthe basis of prevention of that burden (Vogtländer *et al.*, 2001). Eco-costs as described by Vogtländer *et al.* are virtual costs to prevent three major groups of environmental impacts: material depletion; fossil energy consumption; and toxic emissions. Eco-costs are described as marginal prevention cost, related to pollution and material depletion. Eco-costs are virtual costs relate to the cost of measures that must be taken in order to reduce emission to a sustainable level (Vogtlander *et al.*, 2001 & 2006; Yahya and Boussabaine, 2006). The value of eco-costs is the price that must be invested to make, for example CO_2, reduction system to balance the impact of a product or service to the environment. The calculation of eco-cost is done by taking into consideration of both direct and indirect environmental impacts (Vogtlander *et al.*, 2001). The estimation is based on a “what if” condition (Vogtlander *et al.*, 2006). Vogtländer *et al.* (2001) described eco-costs as the sum of:

a) The virtual pollution prevention cost

b) The cost of energy

c) The material depletion cost

d) The cost of depreciation (use) of equipment, buildings, etc.

e) The cost of labour

Eco-cost per value ratio (EVR) model is a model developed by Vogtlander *et al.* (2002) as a practical tool for decision making in order to achieve sustainability and economy. This tool features a single indicator for several environmental impacts (material depletion, energy consumption, and toxic emission) and indicator that show the link between economy and ecology (value chain and ecological product chain). EVR is calculated from the total eco-costs divided by the value or “fair price” of a project as shown below (Vogtlander *et al.*, 2001).

$$EVR = \sum eco\ costs/value \qquad (23)$$

The result from EVR assessment can be used as guidelines to identify the appropriate approaches in minimizing the environmental burden from construction activities (Yahya and Boussabaine, 2006). Low EVR indicates that the product is considered sustainable in the future. Value or fair price of a project or a product is determined by its image, service quality, and product quality while the costs consist of the purchased material, required energy, depreciation, and labor. Profit and tax are the difference between value and costs. Direct eco-costs include the virtual cost of prevention or reducing emission, the eco-cost of energy, and eco-cost of material depletion, while indirect eco-costs include depreciation and labor. Figure 2.21 describes the decomposition of eco-costs.

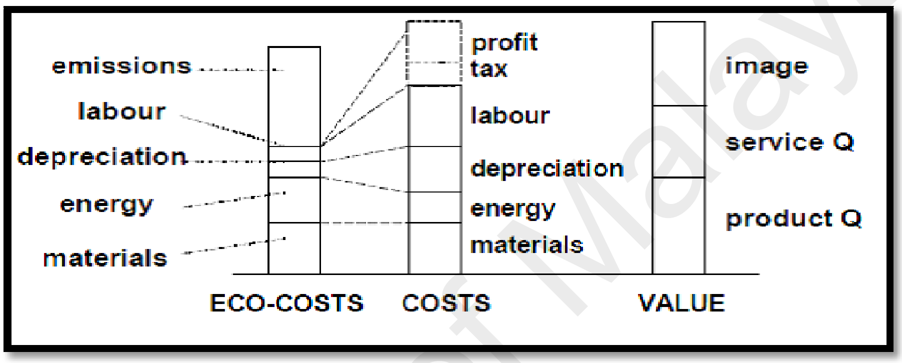


Figure 2.20 Decomposition of 'Virtual Eco-Costs', Costs, and Value of a Product

(Source: Votglander *et al.*, 2001)

In general, calculation of eco-costs elements is conducted according to LCA method as in ISO 14041. For direct costs, firstly the marginal prevention costs, Votglander *et al.* (2001) assessed seven emission effect classes. It was calculated on the basis of prevention measure with readily available technologies. This cost (see Table 2.16) was based on west European 1998 price levels and it is called virtual prevention cost'99. Secondly, eco-cost of energy is calculated based on replacement of fossil energy used by sustainable energy sources. Thirdly, eco-cost of material depletion is approached by assuming to be equal to the raw material market value and applied with a (1-α) factor with α as the fraction of sourced materials that is being recycled as can be seen in equation (24). While eco-costs of depreciation are related to the fact that fixed asset is used to produce a product, the eco-cost of labor varies in the range of 5-15 % of costs for several typical cases (office labor or outside) (Vogtlander *et al.*, 2001).

$$eco\ costs\ material\ depletion = market\ value\ of\ raw\ material\ x\ (1 - \alpha) \quad (24)$$

Table 2.16 Virtual Prevention Cost'99 (Votglander *et al.*, 2006)

Eco-cost	Impact
6,40 Euro/kg	Acidification (as SO_x equivalent)
3,05 Euro/kg	Eutrophication (as PO_4 equivalent)
3,00 Euro/kg	Summer sog (as VOC equivalent)
12,30 Euro/kg	Fine dust for winter smog
680,00 Euro/kg	Heavy metals (as Zn equivalent)
12,30 Euro/kg	Carcinogenics (as PAH equivalent)
0,11 Euro/kg	Global warming (as CO_2 equivalent)

Calculation of eco-costs of depreciation is done similarly to cost estimation for investment as described below (Vogtlander *et al.*, 2001).

$$Eco\ cost\ of\ depreciation = (cost\ of\ depreciation) x\ EVR_{production\ vacility} \quad (25)$$

For construction industry, De Jonge (2005) stated that the calculation of eco-costs for this phase could be done in the same way as the estimation of traditional economic costs, which is by elemental bills of quantities for materials used. The method is related to the fact that the characteristics of building projects are that every project consists of combination of semi-finished products, which are assembled on-site. With this approach, the eco-cost in construction phase is considered as the sum of the eco-costs of semi-finished products as well as the assembling activities. Emission and depletion data for the basis of calculation can be found at database such as IDEMAT and MARKAL. De Jonge (2005) also attempted to calculate the eco-cost of construction labor with the assumption that all the costs of equipment and facilities used by construction workers on building sites are designated to the building site costs while the commuting expenses and the use of service vans, energy for production activities, and working clothes are designated to the cost of labor (Table 2.17).

Table 2.17 EVR for Building Site Costs (Source: De Jonge, 2005)

Cost Factors	EVR
Site facilities and general equipment	0.10
Transportation	0.85
Site management	0.10
Overheads in the building sector (medium sized company)	0.14

There have not been many publications on eco-costing of construction waste. Notable authors in this topic are Yahya and Boussabaine (2006). They concluded that the eco-costs of construction activities will include waste control, recycling and reuse, waste disposal, repair, impact, eco-policy, labor, equipment, emission, and energy with each of this element has its own costs breakdown. The cost structure of eco-costs of the construction waste at the construction stage can be described with the following terms:

$$\sum Cost\ of\ waste\ control, C_{wc} = C_{wc1} + C_{wc2} + C_{wc3} \quad (26)$$

$$\sum Cost\ saving\ of\ recycling\ and\ reuse, C_{rr} = C_{rr1} - (C_{rr2} + C_{rr3}) \quad (27)$$

$$\sum Cost\ of\ waste\ disposal, C_{wd} = C_{wd1} + C_{wd2} + C_{wd3} \quad (28)$$

$$\sum Cost\ of\ impact, C_i = any\ cost\ of\ damage, accidents, health, losses, etc \quad (29)$$

$$\sum Cost\ of\ eco - policy, C_{ep} = any\ cost\ involving\ taxes, levies, etc., \quad (30)$$

$$\sum Cost\ of\ energy, C_e = \sum C_{ei}, i = 1\ ton\ (energy\ consumption), \quad (31)$$

$$\sum Cost\ of\ emission, C_{em} = cost\ \ emissions\ from\ equipment\ use\ on\ site \quad (32)$$

$$\sum Cost\ of\ depreciation, C_{de} = depreciation\ cost\ of\ equipment\ on\ site \quad (33)$$

$$\sum Cost\ related\ to\ labour, C_{lab} = any\ cost\ related\ to\ labour\ on\ site. \quad (34)$$

$$Total\ eco\ costs = C_{wc} + C_{wd} + C_{ep} + C_e + C_{rr} + C_i + C_{em} + C_{de} + C_{lab} \quad (35)$$

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter highlights and elaborates the research methodology conducted in this study. Figure 3.1 overviews a series of methodological sequence employed in this study. Each component shall be elaborated and discussed further in the next sections. Data analysis element comprises of two sections which are waste quantification, and impact assessments. The results of these evaluations are presented in Chapter 4 and further evaluation and discussion are presented in Chapter 5.

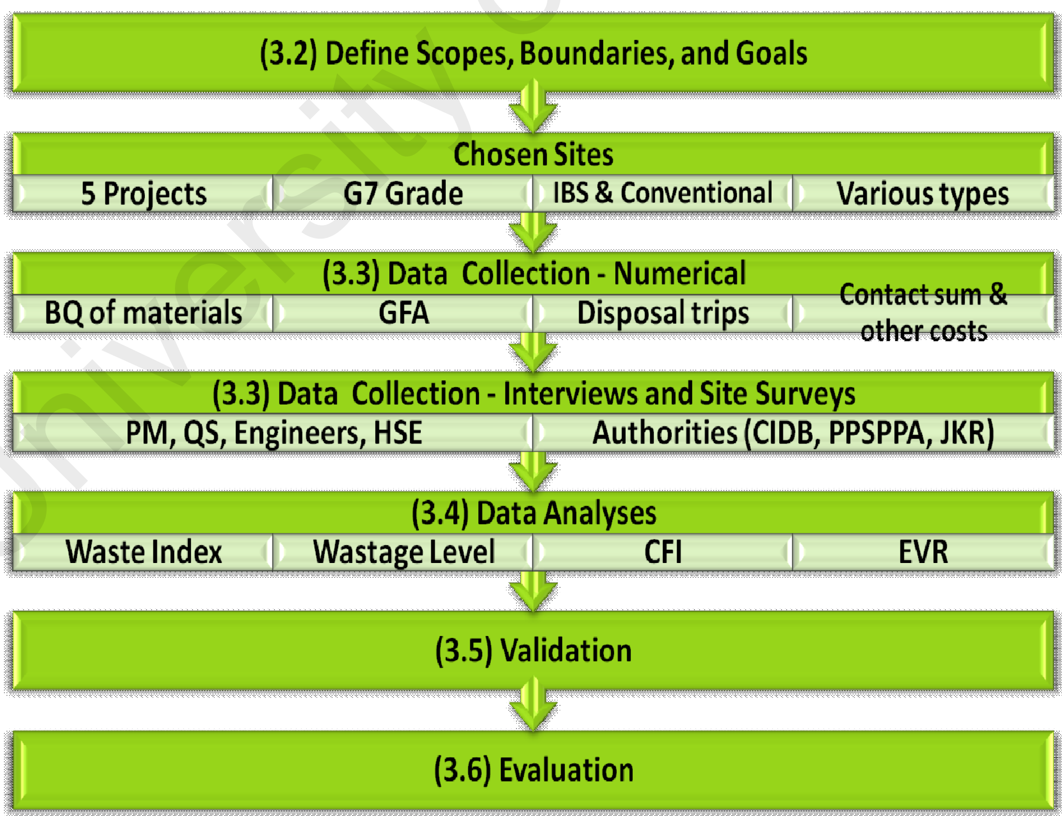


Figure 3.1 Research Methodology Flowcharts

3.2 Scope, Boundaries, and Goal

Five projects in Klang Valley constructed between 2009 through 2010 had been selected for this study, which mainly include institutional, residential, and commercial building projects conducted by a wide range of contractors employing conventional and IBS systems. Conventional timber (and also plywood) formwork has been the backbone of construction method in Malaysia for many years, but IBS systems have started to gain some acceptance and encouragement from government, although it is only limited to a small number of larger contractors. The majority of IBS systems employed are metal formwork system (steel or aluminum), and precast concrete system (for columns, beams, slabs, and wall) which are believed to relatively produce less waste. Most of the main contractors were G-7 Grade under Malaysian CIDB (Construction Industry Development Board) grading system.

Wastage level and waste index approaches had been employed in this study as tools for quantifying waste and also for environmental assessment. Wastage level and construction waste index concepts was first introduced by Poon *et al.* in 2001 to establish benchmark data in Hong Kong's construction industry (Poon, 2001b). Environmental impact assessments were carried out afterwards by employing carbon footprint index (CFI) and eco-costs/value ratio (EVR) tools. These are simplifications of LCA scope in order to consider key impact assessments, i.e. global warming. Carbon footprint term is currently quite popular and global warming awareness has gained wide range of acceptance in many industries. While eco-costing is a relatively novel approach in LCA study and it ought to be implemented in construction waste assessment. These assessments were carried out for selected project sites to achieve comparable results and to establish benchmarks for current status in construction waste generation for Malaysian context, especially Klang Valley.

Types of waste that generated at significant amount, such as concrete, timber, reinforcement bars, brick and blocks, tiles, finishing waste from tiling, screeding, and plastering are considered. Other factors, such as waste management provision, Environmental Management System (EMS) employed, record-keeping, contractors' profile and other related matters are also assessed by conducting interviews with construction personnel.

Since there were only five construction projects selected for this study, some limitations and constraints were found, particularly in regards to accuracy of data validation by employing correlation analyses. Nevertheless, selected projects cover the research scope, which consist of projects with various degrees of IBS implementation and various types of buildings, i.e. residential, commercial, and institutional.

3.3 Data Collection

This study will only focus on waste index, wastage level, carbon emissions and eco-costs for waste generated during construction phase, not the full life cycle. Major construction materials such as concrete, timber, reinforcement bars, brick and blocks, tiles, and plaster/mortars were taken into account. Only waste generated from construction activities at superstructure phase was considered since most of waste is generated during this phase. Waste generated from substructure and foundation works are considered minimum which consisted of mostly excavated soil (Poon *et al.*, 2001b). Construction projects covered in data collection process were high rise and low rise residential, commercial, high rise and low rise institutional buildings employing conventional and IBS systems within Klang Valley area.

LCA analysis will be conducted by reducing the complexity of product system boundary. The objective is limited to identification and measurements of key impacts, i.e. toxic emissions, material depletion, and fuel consumption. For carbon footprint analysis, unit composition of listed CO_2 emissions (kg CO_2-equivalent emission) for various construction materials available from the literatures will be used as the inventory database of carbon footprint assessment, which is needed to quantify CO_2 emissions generated from construction waste. Global warming impact assessment will refer to Life Cycle Inventory (LCI) database. The main objective was to compare the total amount of debris and the percentage of total material quantities wasted during construction process according to type of building, size of project, construction system employed, contractors' policies and waste management practice, likely sources and causes of waste.

Data used for the study was collected in three ways: interviews with key personnel, observational site visit, and reviews of project documentation and established data. The participants in interview sessions included HSE/Environmental Officer, Quantity Surveyors (QS), Engineers, and even Project Manager as on-site representatives for respective projects. In addition, the author was required to liaise with a number of government agencies in Federal Territory and Selangor State which directly concern with construction industry and public solid waste, particularly, the Ministry of Works (JKR), and *Solid Waste Management and Public Cleansing Agency* or *Perbadanan Pengurusan Sisa Pepejal dan Pembersihan Awam* (PPSPPA) which falls under the Ministry of Housing and Local Government. Official permission and approval from JKR were required for some government projects in order to proceed with data collection process.

Since most building contractors outsourced waste disposal and landfilling to third-party disposal lorry companies, some telephone interviews were set up with the subcontractors to obtain more information and general view of the operation, including the disposal fees charge, exact volume of waste bin for each lorry, and location of landfill area. Normally, the volume of waste bin for construction debris disposal was

7.56 m^3, depending on the various lorry fleet owned by the companies as can be seen in Figure 3.2. There were some projects that employed smaller (about 5 m^3) or larger lorry. Most disposal companies charged disposal fees based on the number of trip, some by daily rate basis with extra rate for overtime. The fees were ranging between RM 150 – RM 250 per trip. Dengkil was the designated landfill area appointed by the authority (PPSPPA) for Klang Valley. According to PPSPA, landfill tipping fees charged was RM 200 per m^3 or RM 150 per tonne.

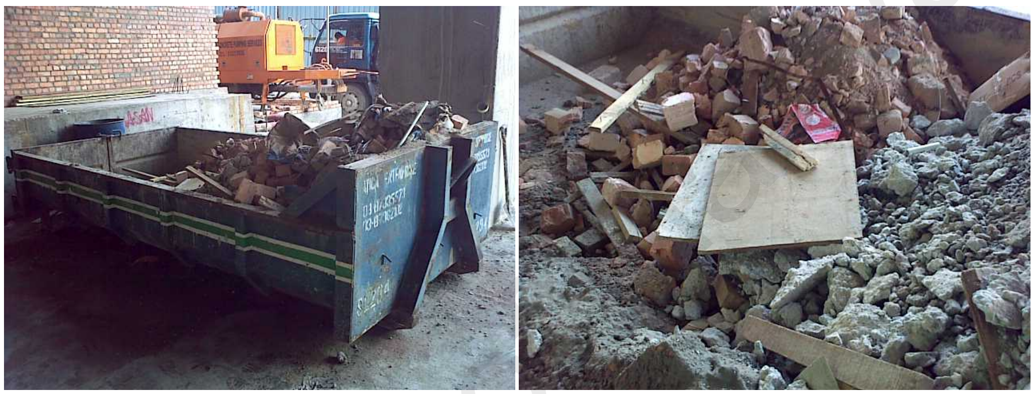


Figure 3.2 Construction Debris Waste Bin

Interview and meeting sessions (including occasional site visit) with PPSPPA were carried out to gain information such as landfill tipping fee, and other established data such as common waste disposal contractors and disposal trips record for a number of completed projects for comparison and benchmarking purposes. With the contractors, interviews were conducted periodically for several times during the course of construction. The researchers used a written questionnaire to conduct interviews. The questionnaire was composed of questions that solicited information regarding: the participant's awareness, knowledge, and experience on waste generation, waste management, IBS system, and even suggestions for the respective or previous projects. The questionnaire used during the data collection process contained the following questions:

1. What is the contractors CIDB grade?
2. Is this contractor adopting ISO14001 certification?
3. Is this project adopting provision on material handling and storage?
4. Is this project adopting Waste Management Plan (WMP)?
5. What construction activities that generate significant amount of waste?
6. Describe what are the main causes of waste generation and their likelihood?
7. Describe what are the key issues that determine the waste generation of a particular project?
8. From your experience, describe the effective measures for waste minimization and management?
9. Describe the IBS system used in this project and why?
10. If project do not utilize IBS system, describe the problems faced in implementing IBS?
11. How much do you roughly spend for waste management purposes in regards to overall project cost?

The interview sessions were often conducted in the general contractor's office trailer on-site. Sometimes, the sessions were carried out at corporate office. In addition to interview sessions, project documentation, raw data, and other records (mainly from Bills of Quantity) were obtained, usually from the QS, and reviewed. Major data extracted include: Gross Floor Area (GFA); material order quantities and material workdone quantities from Bills of Quantity (BQ); construction debris disposal trip record; purchase and delivery costs; and costs associated with waste generation; total project cost (contract sum). Eco-costs considered in this study include: the product unit cost, delivery cost/unit, cost of recycling/salvaging, cost of waste disposal, cost of landfilling (acquired from the Solid Waste Management and Public Cleansing Agency or *Perbadanan Pengurusan Sisa Pepejal dan Pembersihan Awam*, PPSPPA), cost of labor for waste collecting and sorting cost, including cost of implementing corporate policy on waste management. Cost of energy; cost of equipment's emission; and cost of depreciation of equipment would not be considered as performed by Yahya and Boussabine (2006) due to lack of available data and these subjects should be discussed in a different study. All quantitative data and interview result were then summarized in a simple data form which can highlight a general picture of the study aims. Example of data collection form used is presented in **Appendix A.**

Additional data were also obtained from PPSPPA for a number of completed projects which comprise of type of building, GFA, and total number of disposal trips only (other details such as BQ records for materials ordered and waste management practice are not available). Given data were extracted from mostly high rise governmental residential and landed residential (bungalows) using conventional construction method. These data serve as waste index comparison and benchmarking purposes only which is based on type of building. This secondary data is useful for waste index benchmark validation since the combined sample size is quite large, covering a range types of buildings. Given data from PPSPPA would not be taken into account for thorough analysis and further assessment in this study since no interview sessions, site visits, and data collection ever took place during construction phase from each of the respected site.

3.4 Data Analysis

Poon's waste index and wastage level were selected for waste quantification model due to their simplicity, versatility, and reliability incurrent application and data collection process. This is very suitable quantification model to assess the extent of wastage and for implementation in developing country like Malaysia. Advanced models proposed by Jalali (2006), Soliz-Guzman (2009) and Llatas (2011) require established national database and detailed standardization which require stringent enforcement and monitoring from authorities. These quantification models would be time/resources-consuming and very difficult to implement in developing country like Malaysia, whereby there are inconsistencies among contractors in terms of record keeping, and data availability. Other difficulties include lack of established national waste database, standardization among industry players and associated stakeholders, and long terms policies from authorities.

Carbon Footprint Index can be considered as novelty in evaluating the carbon footprint emission and global warming impact potential due to waste generation from various sizes of building projects. This study shall also present the ideal exercise for implementing Eco-costs/Value Ratio (EVR) evaluation for construction waste generation. These assessment tools are improvisations of the current LCA studies to present key impact assessments in index terms for performance evaluation and comparison purposes. Definition of utilized analysis tools is elaborated as follows:

- Waste Index: Actual amount of mixed construction debris produced per total GFA of a project
- Wastage Level: Theoretical estimates of waste amount for each material based on the difference between cumulative order quantity and workdone
- Carbon Footprint Index (CFI): Theoretical estimates for global warming impact potential indicator which described as cumulative amount of carbon dioxide produced per total GFA of a completed project
- Eco-costs/Value Ratio (EVR):A practical tool for decision making which features a single indicator for level of sustainability that shows the link between economy and ecology/environmental impacts.

Analyses methods for calculating waste index, wastage level, carbon footprint index, and EVR are as follow:

1. **Waste Index**

Waste index will help the project manager develop good planning on resources and environmental management and to reduce waste generation during all stages of a construction project. For that reason, the requirement of waste index is to identify the total amount of debris generated per GFA for each construction site (Poon *et al.*, 2001b).

V = truck volume (m³)

N = total number of loads for waste proposal

W = total waste generated by the project (m³) = (V) x (N)

C = Waste index = W / GFA *(36)*

(i.e 1m² area of GFA generates C m³ of waste)

2. **Wastage Level**

The purpose of calculating wastage level is to estimate the quantity of wastage based on total order/used quantities extracted from BQ collected for each individually specified material. Wastage level assessment estimates material-wise "theoretical waste amount" for a given project. Actual waste amount based on individual material shall be almost impossible to quantify as waste will end up in mixed debris. Based on this information, amount of carbon footprint for each specified material, the direct cost of materials wastage and the consequent cost of waste removal and treatment, for example, sorting can be calculated for the purpose of environmental assessment and cost control. Thus, wastage level evaluation is very crucial for carbon footprint and eco-cost assessments. Formula to quantify wastage level which popularized by Poon *et al.* (2001b) is as follows:

(1) Cumulative order quantity

(2) Cumulative workdone

(3) = (1) – (2) = wastage *(37)*

Wastage Level = (3) / (2) x 100 % (including disposed and reused materials) *(38)*

3. Carbon Footprint Index (CFI)

The main scope of this particular study was to assess the impact (greenhouse gas) from building construction activities. Five projects were chosen as per previous objectives. In addition to assessing the environmental impacts generated, carbon footprint index (CFI) of construction process was also quantified to rate the performance of each project. Assessments were made for construction phase until waste generation only, instead of the entire life cycle (Cradle-to-Gate). Studies have shown that construction phase of a building emitssignificant amount of carbon emission in a relatively short time horizon (Säynäjoki *et al.*, 2011).

The first step in quantifying the carbon footprint is to determine the amount of wastage generated for each specified material which is derived from wastage level calculation as described in *equation (37)* above.

Wastage = Cumulative Order Quantity – Cumulative Workdone *(39)*

The next step is to quantify the carbon dioxide produced, by multiplying the amount of wastage by global warming potential (GWP), which is an emission factor, for specified individual material extracted from the LCI database.

Carbon Footprint = Wastage (tonne) x GWP (Equivalent kg-CO_2/tonne) *(40)*

The next step is to determine the total carbon emissions from a single construction project by summing up carbon footprints for all specified materials. In this study, only major construction materials (concrete, timber, reinforcement bars, bricks and blocks, tiles, and plaster/mortars) were considered. Finally, carbon footprint index (CFI) which is defined as the amount of carbon dioxide produced for every square meter of GFA, can be obtained by:

$$CFI = \sum CF/GFA \qquad (41)$$

(GFA) = Total Gross Floor Area (m^2)

($\sum$CF) = Cumulative Carbon Footprint (kg CO_2)

(CFI) = Carbon Footprint Index (kg CO2/ m^2)

The key to achieve ideal carbon footprint calculation involves detailed data inventory of materials and appropriate LCI databases. LCI database contains the values of global warming potential (GWP) for wide variety of materials obtained through comprehensive LCA study which takes time and costly because each type of material used has a complex life cycle. Some adjustments were made to overcome some limitations encountered in this calculation. National LCI Database for Malaysian context has yet to exist; therefore, database utilized in this study were taken from Ecoinvent (Switzerland) and Idemat (Netherland). Idemat was established by TU Delft. These LCI Databases are available online (lists can be downloaded for free). Moreover, the databases are fairly complete and comprehensive (industry-specific), with the number of datasets for Ecoinvent and Idemat LCI are more than 4000and 900, respectively (Curran and Notten, 2006).

Several other limitations, besides LCI mismatch, can also lower the level of accuracy for calculated carbon footprint index. In the case of discrepancy of measurement unit in the database with empirical data, unit conversion is needed. Conversion factors used include: density, surface area in length and width, and thickness. Another limitation is the lack of material descriptions. For example, type of cement used is usually unknown, so it was assumed the type of cement used is Portland cement. Similarly, although there are various types of concrete grade, for this study, concrete grade used for each project is assumed the same. This is due to Ecoinvent and Idemat LCI databases which have no GWP values for specific grade of concrete material. GWP for concrete material in normal quality is 261.244 kg CO_2/m^3 (Ecoinvent, 2010).

For timber waste, type of timber used is assumed as plywood. Plywood is widely used for casting concrete in conventional construction method. Again, unit conversion was needed due to discrepancy. For example, in one of the project data obtained, plywood wastage was recorded in unit pieces instead of unit weight. To convert this unit, information on dimension and density of plywood are needed. Dimension for typical plywood is assumed as 2400 mm of length, 1200 mm of width, and 21 mm of thickness (www.cps.gov.on.ca, 2011). Density for plywood was assumed as 10.4 kg/m^2 or 600 kg/m^3 (Idemat, 2010).

For reinforcement bars, data needed is in unit weight (kg), while data obtained was in unit volume. For conversion, information on general density for reinforcing steel was needed. Density for reinforcement steel was assumed 7,849 kg/m^3 (Idemat, 2010). For conventional building, bricks and blocks are normally used, although some projects used gypsum board widely instead of bricks. LCI value for gypsum board is 0.35 $kgCO_2/kg$ material (Ecoinvent2010). The density and thickness of gypsum plaster board were assumed 10.2 $kg/m^2$and 1/2 inch, respectively (Gypsum Association, 2011). For bricks and blocks, LCI databases use unit of weight instead of unit of volume. For conversion, dimension of a brick was assumed as 216 mm of length, 100 mm of width, and 67 mm of thickness. The density of bricks and blocks is assumed to be 1800 kg/m^3 (Ong, 2009).

Cement is used extensively in concrete construction nowadays. Cement industry is one of the sectors that contribute most to climate change, accounting for roughly 5%

of the total CO_2 emissions worldwide (Humphreys and Mahasenan, 2002).The environmental impact of these products is quite enormous because these products typically make up 40-60% of the total weight of a conventional concrete building.For carbon footprint calculation, it was assumed that type of cement used is Portland cement, which is the most popular type of cement. GWP for Portland cement was 0.72 $kgCO_2$/kg material (Idemat, 2010).

4. Eco-Costs/Value Ratio (EVR)

The purpose of EVR calculation is to determine the sustainability level of a construction project. It is a measure of the environmental burden of a project. EVR calculation can be done for the entire life-cycle of a building or for only a certain phase such as the construction phase, as the case for this study. Moreover, the EVR study conducted in this study was only accounted for those related to on-site generation of construction waste.

According to Yahya and Boussabaine (2006), eco-costs of construction waste are a subset of environmental costs associated with construction site activities where all attributes in the equation, described in literature review should be taken account when quantifying the eco-costs. However, due to limitation of data provided, eco-costs considered in this study only include the product and delivery cost/unit, cost of disposal, cost of land filling, and cost of labor for waste collecting and sorting cost. This study shall assess eco-costs as the result or consequences of waste produced. Similar to carbon footprint index (CFI) assessment, wastage level calculation, as previously described in *equation (37)* above, will be the basis for most of eco-costs evaluation. The calculations for each cost are as follow:

1. Unit Cost and Delivery Cost

Unit Cost = Wastage x Unit Purchased x Purchased Cost *(42)*

Purchased costs are taken from the data provided by courtesy of Commerce House Sdn Bhd. It is important to note that the delivery unit cost was already included in Price list.

2. Labor Cost

Labor Cost = No of labor needed/week x Length of work x Cost per labor *(43)*

Based on information obtained from most interview sessions, it was found that the number of labor required per week for housekeeping and waste handling was assumed to be ten people per week, and the cost per labor is assumed to be the same of average wage for general construction worker-building in Kuala Lumpur which is RM 50/day/person.

3. Total Disposal Trip Cost

Total Disposal Trip Cost = Number of trip x Cost per trip *(44)*

Construction projects taken as case studies shall acknowledged as Project A, Project B, Project C, Project D, and Project E, hereafter. Cost per trip data is provided for project B. Other project cost is assumed to be the same as project B as for a range of length, cost for a trip is relatively the same. Project D is an exception where the total disposal trip is already provided. Data for the number of trips shall be extracted from waste index calculation.

4. Landfilling Cost

Landfilling Cost = Total Waste Volume x Cost per Volume *(45)*

Based on data obtained from *Perbadanan Pengurusan Sisa Pepejal & Pembersihan Awam* (PPSPPA) or Solid Waste Management and Public Cleansing Agency, land filling cost is assumed as RM 200 per m^3 of waste. Data for total waste volume shall also be extracted from waste index calculation.

Thus, EVR can be described in the following terms.

EVR = ∑[Unit & Delivery Costs + Labor Cost + Disposal Cost + Landfilling Cost] (RM)/Total Project Cost (RM) *(46)*

Although this study did not fully include all attributes proposed by Yahya and Boussabine (2006), it was expected that the costs considered in this study shall represent the eco-costs of each project objectively. This is because the cost attributes are not considered in this calculation such as the cost of impacts, cost of emission from equipments, and cost of depreciation of equipment are minor compared to the major costs considered.

3.5 Data Validation

Statistical correlation was conducted for data and result presented which employed using Microsoft Excel as a tool. Correlation analysis was conducted using Pearson Product – Moment Correlation. Pearson Product – Moment Correlation is one of the measures of correlation which quantifies the strength as well as direction of such relationship (Choudhury, 2009). In the study of relationships, two variables are said to be correlated if change in one variable is accompanied by change in the other – either in the same or reverse direction. This coefficient is used if two conditions are satisfied: the variables are in the interval or ratio scale of measurement; and a linear relationship between them is suspected.

The coefficient (r) is computed as the ratio of covariance between the variables to the product of their standard deviations. This formulation is advantageous. First, it indicates the direction of relationship. Once the coefficient is computed, (r) > 0 will indicate positive relationship, (r) < 0 will indicate negative relationship while (r) = 0 indicates non-existence of any relationship.

Second, it ensures (mathematically) that the numerical value of r range from -1.0 to +1.0. This enables us to get an idea of the strength of relationship, or rather the strength of linear relationship between the variables. Closer the coefficients are to +1.0 or –1.0, greater is the strength of the linear relationship (Table 3.1).

Table 3.1 Correlation Coefficient Values and Strength of Relationship

Value of (R)	Strength of Relationship
-1.0 to –0.5 or 1.0 to 0.5	Strong
-0.5 to –0.3 or 0.3 to 0.5	Moderate
-0.3 to –0.1 or 0.1 to 0.3	Weak
–0.1 to 0.1	None or very weak

This measure of correlation has interesting properties, some of which are enunciated below:

- It is independent of the units of measurement.
- It is symmetric. This means that (r) between X and Y is exactly the same as (r) between Y and X.
- If the variables are independent of each other, then one would obtain (r) = 0.

3.6 Evaluation and Interpretation of Result

Validated outcomes of study are evaluated in Chapter 4 – Result and Analysis. Further interpretation and discussion are covered in Chapter 5 – Discussion. Interpretation of result and discussion are elaborated based on comparison and current trends from previous studies, current scope, goals of study, and recommendation to improve sustainability of Malaysian construction industry.

Four instruments were chosen in order to integrate different level of assessments and also to show integration between construction waste management (waste index and wastage level) with sustainability of construction projects as shown by CFI and EVR indices.

These instruments will be beneficial for the development of national database structure and/or to support the implementation of “green” policies in the future, such as the Malaysia’s Green Building Index (GBI hereafter) rating system. Findings from this study can facilitate and complement the GBI requirements as GBI certification dictates contractors to achieve sustainable building design and practices through scoring system.

CHAPTER 4

RESULTS AND ANALYSES

4.1 Introduction

This chapter presents the result from the entire assessment tools for all selected various project sites covered in this study and how they correlate and their implications within each tool. These assessment tools featured in this study would also satisfy the proposed research objectives mentioned in the first chapter. Waste index and wastage level will be presented in sub-chapter 4.2.

The result for carbon footprint index (CFI) and eco-costs per value ratio (EVR) assessments from construction waste generation shall highlight the sustainability level revealed from a given building during its construction phase. CFI and EVR result will attempt to represent the environmental impacts of construction waste described in quantitative measures. Result from construction waste CFI and EVR assessments will be presented in sub-chapter 4.3 and 4.4, respectively. While statistical correlation for data and result validation will be presented in sub-chapter 4.5.

4.2 Waste Index and Wastage Level Assessments

Conclusively, Waste Index and Wastage Level are indicators for the extent of wastage for a given project which demonstrate the sum of physically produced wastage that arises, not only for individually specified materials but also for the total quantity of debris that would eventually been transported and disposed off at designated landfills. The extent of wastage produced for a given project determined heavily by the characteristics of a building and the quality of waste management demonstrated by the contractor. Waste index and wastage level are practical and straightforward assessment tools introduced by Poon *et al.* in 2001. Result from waste index and wastage level assessments for selected project sites are presented in Table 4.1.

As mentioned earlier in Chapter 3, additional complementary data were provided by PPSPPA authority for a number of completed projects within Klang Valley. Given data were extracted from mostly high rise governmental residential and landed residential (bungalows) using conventional construction method as displayed in Table 4.2 and 4.3. Both tables and data presented solely serve as waste index comparison and benchmarking purposes only since only GFA and number of disposal trips data was available. Data shown in Table 4.2 and 4.3 are not part of the study conducted.

Table 4.1 Waste Index and Wastage Level Assessments for Chosen Sites in Klang Valley

Project	A	B	C	D	E
Contractor	**Y**	**Z**	**X**	**X**	**V**
CIDB Grade	G7	G7	G7	G7	G7
Type of building	Low Rise Institutional& Office, 4 storey	High Rise Institutional& Office, 12 storey	Low-Rise Commercial, 4 storey	High-End & High Rise Residential (Condominium)	Low Rise Institutional, 6 storey
Method	Conventional (plywood)	Semi-IBS (f.work system) for columns & slabs, conventional for the rest	Mostly conventional, small portion using f.work system for columns (Minor IBS)	Fully composite IBS (precast panels as permanent f.work from PERI; f.work system for slabs from Kumkang),	Conventional
Duration	Nov 2008 – Nov 2010 (24 Months)	Oct 2008 – Oct 2010 (24 Months)	April 2008 – June 2010 (26 Months)	Jan 2006 – Dec 2010 (59 Months)	Jan 2009 – Jan 2011 (24 Months)
GFA (m^2)	17,000	15,800	143,600	123,002	15,000
Waste index (m^3/m^2)	**0.0339**	**0.0488**	**0.1087**	**0.1497**	**0.06804**
Wastage Level	**Rebar 5.15%, concrete 10.54 %, timber 100%, bricks & blocks 5.19%, plaster 8.03%, tiles 8.00%**	**Rebar 10.34%, concrete 10.20%, timber 100%, bricks 4.87%, cement 3.36%, tiles 3.20%, sand 6.01%**	**Rebar 5.71%, concrete 5.26%, timber 100%, bricks & blocks 3.63%**	**Rebar 9.63%, concrete 4.41%, timber 100%, bricks 5.06%, blocks 5.23%, cement 1.59%**	**Rebar 7.69%, concrete 1.01%, timber 9.77%, bricks & blocks 3.45%, plaster 8.09%, tiles 7.17%**
Waste Management	Rebar & metals were reused & salvaged, some concrete waste	Rebar & metals were reused & salvaged, some concrete waste	Rebar & metals were salvaged,	Rebar & metals were salvaged,	Rebar & metals were reused & salvaged, concrete waste reused,

Project	A	B	C	D	E
	buried, timber reused & burnt, other light waste salvaged or burnt	from piling buried			timber reused & some are recycled
Lifespan of materials	Timber → 2 times	Timber → up to 4 times	Timber → up to 4 times	Timber → 4-6 times	Timber → 5-6 times, some recycled
Profile					

Table 4.2 Waste Index Values for High Rise Buildings in Klang Valley (Source: Based On Given Data from PPSPPA)

Project	**1**	**2**	**3**	**4**	**5**
Contractor	N.A	N.A	N.A	N.A	N.A
CIDB Grade	N.A	N.A	N.A	N.A	N.A
Type of building	High Rise Residential, 548 units	High Rise Residential, 426 units	High Rise Commercial, 12 storey	High Rise Residential, 15 storey	Low Rise Residential, 3 block, 5 storey
Method	Conventional	Conventional	Conventional	Conventional	Conventional
Duration	Sep 2008 – Jan 2010	July 2008 – Dec 2009	July 2009 – September 2010	Nov 2009 – Oct 2010	May 2009 – April 2010
GFA (m^2)	**66,253**	**29,713.5**	**25,827.6**	**29,778**	**28,020**
Waste index (m^3/m^2)	**0.0387**	**0.0733**	**0.0520**	**0.0438**	**0.0466**
Wastage Level	N.A	N.A	N.A	N.A	N.A

Table 4.3 Waste Index Values for Landed Housing in Klang Valley (Source: Based On Given Data from PPSPPA)

Project	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Contractor	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A
CIDB Grade	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A
Type of building	Landed Residential	Landed Residential	Landed Residential	Landed Residential	Landed Residential	Landed Residential	Landed Residential, 42 units, 2 storey bungalow	Landed Residential, 7 units of 3 storey bungalow	Landed Residential
Method	Conventional	Conventional	Conventional	Conventional	Conventional	Conventional	Conventional	Conventional	Conventional
GFA (m^2)	**418.5**	**251.1**	**251.1**	**446.4**	**457.09**	**615.32**	**2959.2**	**2530**	**500**
Waste index (m^3/m^2)	**0.0738**	**0.0878**	**0.0990**	**0.0557**	**0.0643**	**0.0614**	**0.0649**	**0.0498**	**0.0588**
Wastage Level	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A

From Table 4.1, it was found that project A had the lowest waste index value, which is 0.0339 m^3/m^2 followed by Project B and Project E with 0.0488 m^3/m^2, and 0.06804 m^3/m^2, respectively. Meanwhile, waste index of Project C was 0.1087 m^3/m^2 and Project D had the highest waste index of all with 0.1497 m^3/m^2. From the results, it can be seen that waste index tends to be higher for large and tall building projects, as proven in Project D, which was a 50-plus storey building, consists of three towers, and vast GFA of 123,000 m^2.Project C, which was a shopping mall, although had higher GFA than Project D, was a 4-storey building, single block, and without basement. Project A, B, and E had more or less similar floor area which produced almost similar waste index values. Project A had the lowest waste index among project studied since it was low rise building with only 4-storey height and no basement.

From this evaluation as outlined in Table 4.1, it can be highlighted that waste index value was independent to construction method. Most prominent prove is shown in Project D which was utilizing full IBS method and yet produced the highest waste index. Project A, which had the lowest waste index value, was adopting conventional method as also shown by Project E.

However, waste index result showed some particular trend in terms of type of building. From waste index evaluation, it can be highlighted that institutional buildings, in this case Project A, B, and E, showed lower waste index values compared to Project C (commercial) and Project D (residential). However, inadvertently, institutional projects featured in this study were considered as small-scaled, in terms of total floor area and project cost. Thus, more studies and evaluations should be carried out to determine the correlation between waste index and type of building.

Meanwhile, wastage level result showed extreme values for each construction waste materials among featured projects. Concrete wastage level contributes as high as 10.54% in Project A and as low as 1.01% in Project E. Rebars wastage were around 5%

in Project A and C, but reached 10% in Project B and D. Since timber is used as temporary formworks, this material most likely ends up as waste after an average usage of four times. Project E exhibit a rare example of timber recycling and timber utilization as part of the buildings' permanent structural and finishing elements, which reduced timber wastage by up to 10% instead of 100% even though this project utilized conventional method. Used timber was sorted and collected prior to salvaging by recyclers. Leftover timber scraps shall end up to be disposed off. This practice helps to significantly reduce timber wastage. Bricks and blocks were the only material with comparable wastage level among the projects studied, with an average of 4%. Data on tile wastage were only available in Project A, B, and E, which reached as high as 8% due to their proneness to damage caused by mishandling or unavoidable cutting. Similarly, plaster could also reached 8% of wastage as showed in Project A and E due to unavoidable spillages.

In terms of waste management, all projects mostly carried out similar practices such as reusing timber for temporary formworks purposes, and salvaging used up rebars, which is very common due to resale value of steel. Other approach was in Project A in which waste burial and open burning were practiced. These practices, although could reduce the waste index value, may not be appropriate in high density urban area. This is because, smoke and related air pollution discharge from open burning will cause disruptions and health hazards among nearby inhabitants. Meanwhile, waste burial might result in soil contamination.

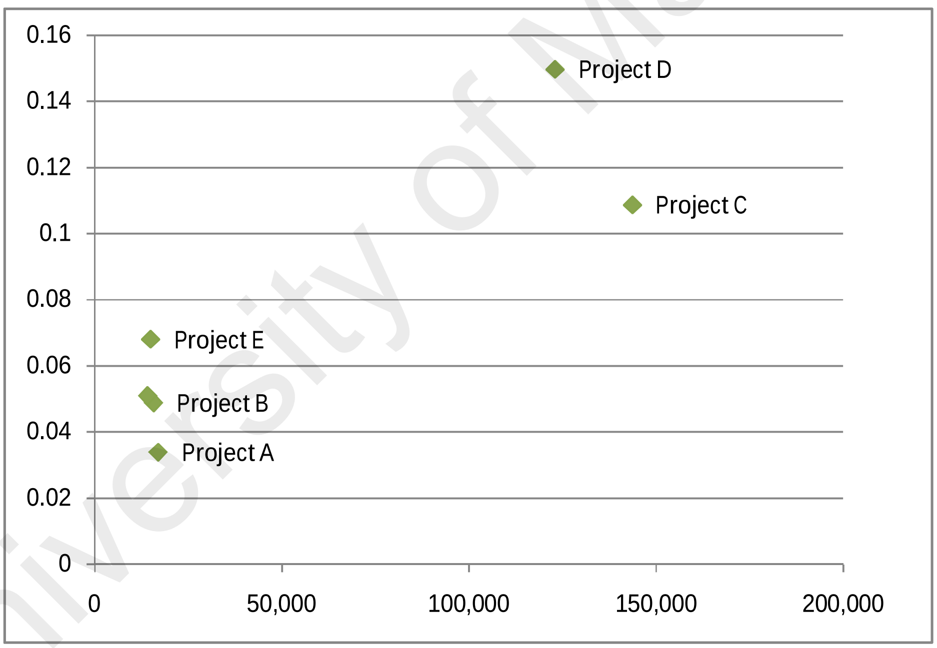
Established and calculated data shown in Table 4.2 indicates that for typical government multi-blocks low to high-rise residential projects using conventional construction system, waste index result were more or less similar to that of institutional buildings (Projects A, B, and E) shown in Table 4.1. These government residential projects were mostly having comparable floor area which considered as small-scaled (below 100,000 m^2). It can be highlighted from Projects 1 – 5 that benchmarks of waste index value for low to high-rise multi storey government residential projects were around 0.04 – 0.05 m^3/m^2.

Similarly, Table 4.3 showed established and calculated data for typical landed housings. These projects were mostly 2 storey high-end bungalows adopting conventional construction method. Result showed that waste index benchmark for landed high-end residential such as bungalows produced slightly higher waste index benchmarks of 0.05 – 0.06 m^3/m^2, compared to low-rise/high-rise government flats. It should be noted that design plays a significant role in contributing waste index values. High-end construction typically undergoes more complicated and aesthetic design which makes them more prone to errors, customization, and more material consumption. For instance, Project 10 and Project 14 were equipped with swimming pools and basement. Low-end government housing typically has uniform design which tends to be easier and quicker to construct and eventually contribute to less waste index.

From the result, it seems that construction method did not show any relationship with waste index. Rather, it was more governed by the waste management practice performed by the contractor, design, and size of the respected projects. As seen in Table 4.1, wastage level for each specified material for each project showed a quite contrast value.

For example, concrete wastage for Project A, and B can be as high as 10% while for Project E was only 1%. All timber used will eventually end up as waste for projects adopting conventional system, except for Project E which managed to utilize timber as part of permanent structure and recycle timber waste as only 10% of which actually is disposed off. But, high wastage level does not necessarily proportional to high waste index value since waste index is determined by the actual amount of debris transported and disposed at landfills. Some wastage material such as rebars can be salvaged for recycling plan, which is quite common practice, some contractor would burn down leftover timber or even bury some concrete or plaster waste.

Project A, B, and E produced low waste index values even though mostly utilized conventional system which contribute significant concrete and timber wastage (100%). Waste index values highlighted in green are quite low due to significantly smaller size of project. Figure 4.1 shows this particular phenomenon. Project C, and D have higher waste index simply because significantly higher quantity of major material usage, especially concrete, rebars, and timber. Large-scale and high-cost constructions like Project C and Project D consumed a great deal of materials due to structural needs such as columns, beams, slabs, and also during finishing stage.



GFA (m^2)

Figure 4.1 GFA vs Waste Index Chart for Chosen Sites

Thus, it can be outlined that waste index would reflect contractors' waste management policies, even though some plans involve illegal practices such as open burning. While wastage level would reflect the contractors' environmental awareness and overall productivity, particularly in commitment to efficiencies in material handling, shipping, labor skills, coordination, and also quality of work. Based on sampled project sites and established data given by PPSPPA, benchmark values for waste index and wastage level in Klang Valley can be summarized in Table 4.4.

Table 4.4 Summary – Benchmark of Waste Generation Rate in Klang Valley

Type of Building	Waste Index (m^3/m^2)	Wastage Level					
		Concrete	Timber	Rebars	Bricks & Blocks	Plaster	Tiles
Landed Residential (Bungalows)	0.0684	1 – 10 % (avg'd 5.5%)	Up to 100 %	5 – 10 % (avg'd 6.2%)	3 – 5 %	4 – 8 %	3 – 8 %
Low Rise Residential (Government)	0.0387 – 0.0466						
High Rise Residential (Government)	0.0519						
High-End Residential (Condominiums)	0.1400 – 0.1500						
Institutional/Offices (Government)	0.0399 – 0.0680						
Commercials	0.1000 – 0.1500						

From the summary, benchmark wastage levels for each specified material should fall around an average of 5 – 6 %, except for timber waste. Low rise residential, educational buildings and governmental/institutional offices have the lowest waste indices. The formers can be considered as low end/low cost projects. Landed and high-rise residential (depending on design and cost) should have slightly higher waste indices. Commercial, high-end office and high-end residential shall produce the highest waste indices, respectively.

In summary, timber has the highest wastage benchmarks of 100%. This is because for conventional projects, timber is consumed in great quantity for temporary formworks and will end up as waste after 3 – 4 times being reuse. Full IBS system, although not utilizing temporary formworks, would still consume timber to an extent for difficult structural portion of building, unusual design, as well as for aesthetic use, which also outline one of the weaknesses of IBS construction method. Rebars and concrete have wastage level of by up to 10%, followed by plaster and tiles from finishing and wet trades activities by up to 8%. Bricks and blocks have had the lowest wastage level benchmark, averaging 4%. Although timber wastage was benchmarked at 100%, waste index for conventional projects would not necessarily higher than IBS projects. This is because types of building and project size also contributed dominant roles on waste index, since it employed different materials or more heterogeneity in materials.

Meanwhile, waste index benchmarks in Klang Valley show that governmental projects (residential and institutional) tend to produce lower waste index. Data showed that high-end projects, even private landed bungalows, would produce higher waste index than low-end buildings simply due to heterogeneity of materials employed, especially during near-completion stage. This is mainly due to aesthetic reasons. These phenomena will be highlighted and discussed further in the next chapter.

4.3 Carbon Footprint Index (CFI) Assessment on Wastage

Carbon footprint is a simplification of LCA studies which assess the impact of manufacturing or industrial activities to global warming. For the context of this study, CFI is an improvised-approach which evaluates the performance of global warming effect for a given building project as a result or consequences of waste generation during construction phase. CFI result for chosen sites in Klang Valley can be recapitulated individually in Table 4.5 – 4.9 and overviewed in Figure 4.2.

Total carbon footprint for Project A is **895,683.33kg CO_2**. Total Gross Floor Area (GFA) of the project is **17,000 m^2**. Thus, the wastage CFI of this project is **52.69 kg CO_2/ m^2.**

Table 4.5 Calculation of Wastage CFI for Project A

List of Materials	**Wastage**		**Wastage Level**	**Carbon Footprint Data**	**Global Warming Potential**		**Carbon Footprint**	**Total Carbon Footprint**	**CFI**
1	2			3	4		5 = 2 * 4	6	7 = 6 / GFA
type	*amount*	*unit*	*%*		*kg CO_2 equiv.*	*unit*	*kg CO_2 emission*	*kg CO_2 emission*	*kg CO_2/ m^2*
Concrete	715.00	m^3	10.54	Ecoinvent2010, concrete, normal	261.24	kg CO_2/ m^3	186,789.57		
Timber	224,040.96	kg	100.00	Idemat2010, plywood, indoor use (600 kg/ m^3)	0.86	kg CO_2/ kg	191,815.19		
Reinforcement Steel	50,000.00	kg	5.15	Ecoinvent2010, reinforcing steel	1.45	kg CO_2/ kg	72,320.76		
Bricks & Blocks	220,640.11	kg	5.19	EcoInvent2010, brick	0.24	kg CO_2/ kg	52,481.42		
Plasters (sand)	710,000.00	kg	8.03	Idemat2010, sand	0.02	kg CO_2/ kg	11,792.11		
Tiles	487,192.32	kg	8.00	Ecoinvent2010, ceramic tiles	0.78	kg CO_2/ kg	380,484.28	895,683.33	**52.69**

Total carbon footprint for Project B is **414,683.01 kg CO_2**. Total Gross Floor Area (GFA) of the project is **15,800m^2**. Thus, the wastage CFI of this project is **26.25 kg CO_2/ m^2.**

Table 4.6 Calculation of Wastage CFI for Project B

List of Materials	Wastage		Wastage Level	Carbon Footprint Data	Global Warming Potential		Carbon Footprint	Total Carbon Footprint	CFI
1	2			3	4		5 = 2 * 4	6	7 = 6 / GFA
type	*amount*	*unit*	*%*		*kg CO_2 equiv.*	*unit*	*kg CO_2 emission*	*kg CO_2 emission*	*kg CO_2/ m^2*
Concrete	644.00	m^3	10.20	Ecoinvent2010, concrete, normal	261.24	kg CO_2/ m^3	168,241.23		
Timber	96,200.00	kg	100.00	Idemat2010, plywood, indoor use (600 kg/ m^3)	0.86	kg CO_2/ kg	82,362.71		
Reinforcement Steel	83,201.00	kg	10.34	Ecoinvent2010, reinforcing steel	1.45	kg CO_2/ kg	120,343.19		
Bricks & Blocks	1,849.52	kg	4.87	EcoInvent2010, brick	0.24	kg CO_2/ kg	439.93		
Cement	14,500.00	kg	3.36	Idemat2010, cement (Portland)	0.72	kg CO_2/ kg	10,413.90		
Tiles	38,020.75	kg	3.20	Ecoinvent2010, ceramic tiles	0.78	kg CO_2/ kg	29,693.20		
Sand	192,000.00	kg	6.01	Idemat2010, sand	0.02	kg CO_2/ kg	3,188.85	414,683.01	**26.25**

Total carbon footprint for Project C is **2,575,028.33 kg CO_2**. Total Gross Floor Area (GFA) of the project is **143,600m^2**. Thus, the wastage CFI of this project is **17.93 kg CO_2/ m^2.**

Table 4.7 Calculation of Wastage CFI for Project C

List of Materials 1	Wastage 2		Wastage Level	Carbon Footprint Data 3	Global Warming Potential 4		Carbon Footprint 5 = 2 * 4	Total Carbon Footprint 6	CFI 7 = 6 / GFA
type	*amount*	*unit*	*%*		*kg CO_2 equiv.*	*unit*	*kg CO_2 emission*	*kg CO_2 emission*	*kg CO_2/ m^2*
Concrete	2,763.00	m^3	5.26	Ecoinvent2010, concrete, normal	261.24	kg CO_2/ m^3	721,817.58		
Timber	1,270,842.00	kg	100.00	Idemat2010, plywood, indoor use (600 kg/ m^3)	0.86	kg CO_2/ kg	1,088,045.69		
Reinforcement Steel	477,000.00	kg	5.71	Ecoinvent2010, reinforcing steel	1.45	kg CO_2/ kg	689,940.04		
Bricks & blocks	316,257.77	kg	3.63	EcoInvent2010, brick	0.24	kg CO_2/ kg	75,225.02	2,575,028.33	**17.93**

Total carbon footprint for Project D is **829,576.81 kg CO_2**. Total Gross Floor Area (GFA) of the project is **123,002.23m^2**. Thus, the wastage CFI of this project is **6.74 kg CO_2/ m^2.**

Table 4.8 Calculation of Wastage CFI for Project D

List of Materials	Wastage		Wastage Level	Carbon Footprint Data	Global Warming Potential		Carbon Footprint	Total Carbon Footprint	CFI
1	2			3	4		5 = 2 * 4	6	7 = 6 / GFA
type	*amount*	*unit*	*%*		*kg CO_2 equiv.*	*unit*	*kg CO_2 emission*	*kg CO_2 emission*	*kg CO_2/ m^2*
Concrete	2,410.00	m^3	4.41	Ecoinvent2010, concrete, normal	261.24	kg CO_2/ m^3	629,598.40		
Timber	107,000.00	kg	100.00	Idemat2010, plywood, indoor use (600 kg/ m^3)	0.86	kg CO_2/ kg	91,609.25		
Reinforcement Steel	886.00	kg	9.63	Ecoinvent2010, reinforcing steel	1.45	kg CO_2/ kg	1,281.52		
Bricks	213,582.60	kg	5.06	EcoInvent2010, brick	0.24	kg CO_2/ kg	50,802.72		
Blocks	104,077.80	kg	5.23	EcoInvent2010, brick	0.24	kg CO_2/ kg	24,755.93		
Cement	43,900.00	kg	1.59	Idemat2010, cement (Portland)	0.72	kg CO_2/ kg	31,528.98	829,576.81	**6.74**

Total carbon footprint for Project E is **323,971.58 kg CO_2**. Total Gross Floor Area (GFA) of the project is **15,000 m^2**. Thus, the wastage CFI for this project is **21.60 kg CO_2/ m^2.**

Table 4.9 Calculation of Wastage CFI for Project E

List of Materials	**Wastage**		**Wastage Level**	**Carbon Footprint Data**	**Global Warming Potential**		**Carbon Footprint**	**Total Carbon Footprint**	**CFI**
1	2			3	4		5 = 2 * 4	6	7 = 6 / GFA
type	*amount*	*unit*	*%*		*kg CO_2 equiv.*	*unit*	*kg CO_2 emission*	*kg CO_2 emission*	*kg CO_2/ m^2*
Concrete	67.44	m^3	1.01	Ecoinvent2010, concrete, normal	261.24	kg CO_2/ m^3	17,618.31		
Timber	12,830.00	kg	9.77	Idemat2010, plywood, indoor use (600 kg/ m^3)	0.86	kg CO_2/ kg	10,984.55		
Reinforcement Steel & other	66,010.00	kg	7.69	Ecoinvent2010, reinforcing steel	1.45	kg CO_2/ kg	95,477.87		
Bricks & Blocks	69,591.51	kg	3.45	EcoInvent2010, brick	0.24	kg CO_2/ kg	16,553.02		
Plasters (sand)	20,800.00	kg	8.09	Idemat2010, sand	0.02	kg CO_2/ kg	345.46		
Tiles	234,313.17	kg	7.17	Ecoinvent2010, ceramic tiles	0.78	kg CO_2/ kg	182,992.37	323,971.58	**21.60**

The term wastage CFI specifically implies the amount of carbon footprint produced per gross floor area as consequence of wastage during construction phase of a project. As explained earlier in previous chapter, wastage CFI is practically governed by individual wastage of specified materials. Wastage is the difference between quantity of materials ordered and quantity of materials used. Based on Table 4.5, concrete wastage would reach 715 m^3, which contributed to 186,789.57 kg of CO_2 emission. Timber wastage reached 224,040.96 kg, which contributed to 191,815.19 kg of CO_2emission. Meanwhile, tiling wastage reached 487,192.32 kg which contributed to 380,484.28 kg of CO_2 emission. Tiles, timber, and concrete wastage were the largest contributor of total carbon footprint generated by Project A, which resulted in 52.69 kg of CO_2/m^2 of CFI. Based on result, large portion of carbon footprint from concrete and tiles were commonly caused by poor handling and design errors, as proven in high wastage levels of 10.54% and 8%, respectively. Although sand wastage for plastering was generated at the largest portion, carbon emission resulted was the lowest due to very low global warming potential (GWP) suggested by LCI database.

From Table 4.6, total carbon emission generated by Project B reached 414,683 kg of CO_2 which contributed to 26.25 kg of CO_2/m^2 of CFI. CFI value for Project B was nearly half of that in Project A. Similar to Project A, sand wastage for plastering was the largest portion of waste generated, but only contributed to only 3,188.85 kg of CO_2 emission. "Big three" materials of concrete, timber, and rebars were major wastage and contributed to 168,241.23 kg CO_2; 82,362.71 kg CO_2; and 120,343.19 kg CO_2, respectively. Result shows that Project B generated less emission from concrete and timber due to considerable portion of IBS implementation. CFI evaluation also reveals that tiling wastage contributed significantly lower carbon footprint than that of Project A, which reflect better material handling, especially during finishing stage.

Based on Table 4.7, CFI evaluation revealed that Project C generated 2,575,028.33 kg of carbon footprint, the largest among five projects studied. However, Project C only produced 17.93 kg of CO_2/m^2 of CFI. Timber was the largest quantity of wastage generated with 1,270,842 kg, which contributed to 1,088,045.69 kg of CO_2 emission; followed by concrete with 721,817.58 kg CO_2; and reinforcement bars with 689,940 kg CO_2. Large portion of carbon footprint from timber wastage was caused by extensive use of conventional system. Although there was an absence of tiles and plaster wastage data, it was believed to have insignificant effect to CFI value since wastage level analysis showed that wastage levels for specified materials in Project C were around 5% and less. This reflects good material handling and waste management features.

Based on Table 4.8, Project D generated 829,576.81 kg CO_2 emission and yet only resulted in 6.74 kg of CO_2/m^2 of CFI. This was the Project with the best performance in terms of CFI, among studied projects. Carbon emission from concrete wastage was the largest portion of total carbon emission with 629,598.40 kg of CO_2. Project D only produced 107,000 kg of timber and 886 kg of rebar wastage, which contributed to 91,609.25 kg of CO_2 emission, and 91,609.25 kg of CO_2 emission, respectively. This was mainly caused by extensive use of full IBS system during structural phase of construction. Bricks and blocks were identified as one of the largest contributor of wastage, but only resulted in small portion of carbon footprint due to small GWP value of bricks.

Based on Table 4.9, Project E generated 323,971.58 kg of CO_2 emission which resulted in CFI value of 21.60 kg of CO_2/m^2. Tiles were identified as the largest portion of waste generated and total carbon footprint with 234,313.17 kg and 182,992.37 kg of CO_2, respectively. Bricks & blocks and rebars made up the second and third largest portion, with 69,591.51 kg and 66,010 kg, respectively. Meanwhile, rebar wastage was the second largest contributor of total carbon footprint with 95,477.87 kg of CO_2. Result from CFI evaluation suggests that Project E was quite similar to Project A, in terms of the largest total carbon footprint, with tile wastage made up the most significant contribution. This shows poor material handling, especially during finishing stage, which is proven by considerably high wastage level value for tiles with up to 8%. However, Project E performed well in timber wastage and CFI, being only produced 10% of wastage level and 11,000 kg of CO_2/m^2 CFI, respectively. This reflects some degree of timber recovery and recycling, and also considerable utilization of timber, permanently as part of the structure and finishing.

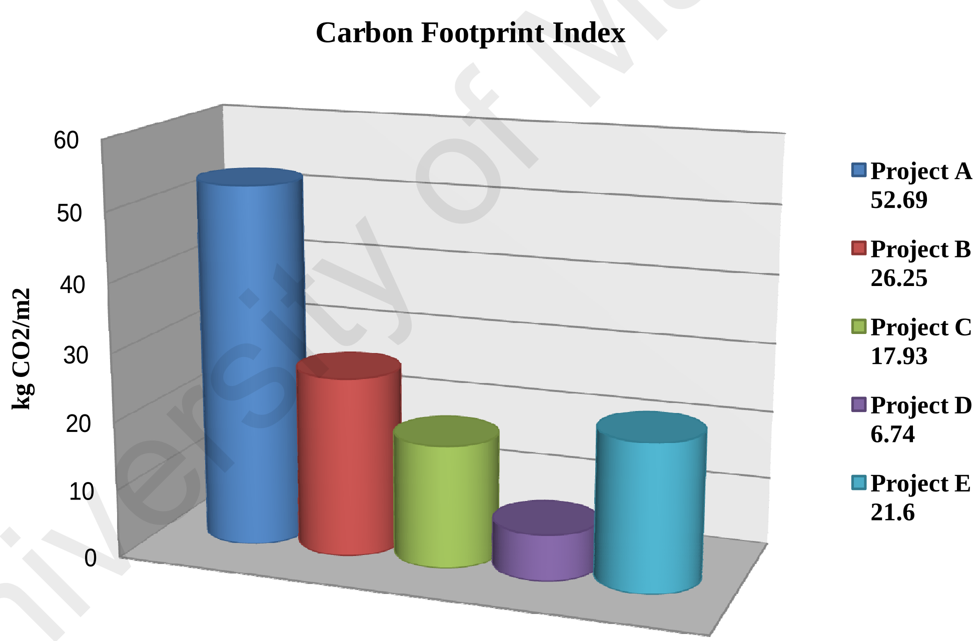


Figure 4.2 Wastage Carbon Footprint Index for Selected Projects

From the result shown above, waste from Project C emitted the most carbon footprint at approximately 2,575 tonnes of CO_2, while waste Project D emitted the least with 830 tonnes of CO_2. It seems that wastage CFI values were heavily determined by method of construction. Project D, which was the largest and costliest project in this study, performed the best in terms of wastage CFI. This is the only project featured in this study which utilized composite IBS systems, including precast structural elements (considered as permanent formwork) and formwork system for slabs. Project C and E also performed well in wastage CFIs due to excellent quality control and waste management practice as shown in wastage levels benchmarks, considering these projects were utilizing conventional method. Project B, which was a high-rise construction, performed fairly well in wastage CFI assessment. Project B implemented a considerable portion of formwork system, which commonly still referred as "semi-IBS" in the industry, for columns and slabs. Project A was the worst performer in carbon footprint release as seen from previous result(high wastage levels for virtually all core materials) as revealed in contractor's poor environmental practice (open burning and illegal dumping).

In conclusion, benchmarks for wastage CFI range between 21 – 26 kg CO_2/m^2 for typical conventional projects and it shall be less for full IBS projects. Based on methodology and the result shown, CFI assessment for waste generated is practically governed by wastage level analysis for each specified material, especially "big three" materials i.e. concrete, timber, and reinforcement steels. These materials have the highest global warming potential (GWP) value. They are also used extensively in construction, and wasted in significant quantity. The use of IBS system (especially precast concrete elements) tends to significantly reduce the use and wastage of these materials.

4.4 Eco-Cost per Value Ratio (EVR) Assessment on Wastage

EVR was first introduced by Vogtlander in 2001 as part of LCA studies using economy-ecology approach, especially for consumer products. However, there are limited publications available on EVR application in construction industry. Eco-costing for construction industry was proposed by Yahya and Boussabine in 2006 which shall encompass as the basis for this study. The result of wastage EVR calculation is presented in Table 4.10 below.

Similar to CFI, EVR results are derived from wastage levels results. Thus, their outcomes shall be greatly determined by wastage levels for each specified materials. It seems that construction method, waste management, and size of project played a major role in EVR outcomes.

Project D which utilized both precast concrete elements and metal formwork system demonstrated a tremendous performance in wastage EVR outcome. This finding proofs that IBS system can substantially reduce the usage of “big three materials” (concrete, timber, and reinforcement steels) and shall greatly decrease these wastages due to improved quality of works and inventory control.

Project C has the largest EVR due to its massive project size. Given that Project C employed mainly conventional system with very small portion of IBS, it produced an enormous amount of generated debris. Large quantity of debris involves more labors for cleaning and sorting purposes, and obviously more disposal trips, thus more land filling cost. As seen on Table 4.10 below, these are the main elements that made up the largest portion of eco-costs incurred by Project C. Pink highlights signify significantly large figures, while green highlight signify lowest figure.

From the finding, it can be concluded that the wastage EVR benchmarks shall fall between 0.0024 – 0.0028 for typical multi-storey projects applying conventional and/or partial IBS, and shall be considerably less for projects utilizing full/composite IBS system or projects with exceptionally good waste management awareness and practice.

Table 4.10 Wastage EVR Result for Chosen Sites in Klang Valley

Project	A	B	C	D	E
Type of building	Low Rise Institutional& Office, 4 storey	High Rise Institutional& Office, 12 storey	Low-Rise Commercial, 4 storey	High-End & High Rise Residential (Condominium)	Low Rise Institutional, 6 storey
Method of Construction	Conventional (plywood)	Semi-IBS (f.work system for columns & slabs, conventional for the rest)	Minor IBS (Mostly conventional, small portion using f.work system)	IBS-composite (precast panels and f.work system for slabs)	Conventional
Duration	Nov 2008 – Nov 2010 (24 Months)	Oct 2008 – Oct 2010 (24 Months)	April 2008 – June 2010 (26 Months)	Jan 2006 – Dec 2010 (59 Months)	Jan 2009 – Jan 2011 (24 Months)
GFA (m^2)	17,000	15,800	143,600	123,002	15,000
Project Value/Cost (RM)	63,500,000.00	37,033,274.60	152,000,000.00	331,450,000.00	31,350,600.71
Total Unit and Delivery Loss (RM)	1,055,193.00	468,813.38	3,110,853.32	1,008,101.29	290,718.89
Total Labor Cost (RM)	364,000.00	364,000.00	1,977,500.00	4,480,000.00	364,000.00
Total Disposal Trip Cost (RM)	15,450.00	15,300.00	209,550.00	756,679.00	20,250.00
Landfilling Cost (RM)	115,360.00	154,224.00	3,121,604.00	204,120.00	204,120.00
Total Eco-Costs (RM)	1,550,003.00	1,002,337.38	8,419,507.32	6,448,900.29	879,088.89
EVR (x 100)	**2.4409496**	**2.7065859**	**5.5391496**	**1.9456631**	**2.8040576**

4.5 Statistical Correlation

Correlation analysis was conducted using Pearson Product – Moment Correlation for validation purpose. This statistical evaluation was performed using Microsoft Excel's correlation analysis tool. Result from each assessment (Waste Index, Wastage Level, CFI, and EVR) are represented as dependent variable X1 – X4. For X2, wastage level, the variables are expanded to X21 – X24 which indicate each waste material produced. Table 4.11 below highlights the list of dependent variables engaged in correlation analysis.

There are two score-based independent variables featured in took part in correlation analysis.Y1 is independent variable scoring based on construction method employed. This signifies the extent and portion of IBS usage of respective projects, Y1 = 1 being 0% of IBS usage (conventional) and Y1 = 4 being fully IBS system (include precast concrete elements). Y2 is independent variable scoring based on the type of project. Y1 and Y2 are highlighted in Table 4.12 and Table 4.13, respectively.

Table 4.11 Analyzed Dependent Variables

Dependent Variable (X)	Remarks
X1	Waste index (m^3/m^2)
X2	Wastage Level
X21	Rebar
X22	Concrete
X23	Timber
X24	Bricks &Blocks
X3	CFI (kg CO_2/ m^2)
X4	EVR (x 100)

Table 4.12 Independent Variable Ranks Based on Construction Methods

Independent Variable (Y1)	Construction Method
1	Conventional (0% IBS)
2	Minor IBS (20-50% IBS)
3	Semi-IBS (60-80% IBS)
4	Full IBS (80-100% IBS)

Table 4.13 Independent Variable Ranks Based on Size of Project

Dependent Variable (Y2)	Type of Project
1	Institutional
2	Commercial
3	Residential

Based on previous outlines, result from the entire assessments of entire selected projects can be integrated and represented statistically in Table 4.14 as follows.

Table 4.14 Value of Each Variable

Project	Y1	Y2	X1	X2				X3	X4
				X21	X22	X23	X24		
A	1	1	0.0339	5.15	10.54	100	5.19	52.69	0.0244
B	3	1	0.0488	10.34	10.2	100	4.87	26.25	0.0271
C	2	2	0.1087	5.71	5.26	100	3.63	17.93	0.0554
D	4	3	0.1497	9.63	4.41	0	5.23	6.74	0.0195
E	1	1	0.0680	7.69	1.01	9.77	3.45	21.6	2.8041

Result from correlation analysis can be illustrated in correlation matrix extracted from Excel, as described in Table 4.15, below. Meanwhile, T- Test was performed to confirm the result of correlation analysis as revealed in Table 4.16, below.

Table 4.15 Correlation Matrix

	X1	**X21**	**X22**	**X23**	**X24**	**X3**	**X4**	**Y1**	**Y2**	**Y2**
X1	1.000									
X21	.260	1.000								
X22	-.542	-.055	1.000							
X23	-.562	-.398	.783	1.000						
X24	-.028	.297	.672	.093	1.000					
X3	-.855	-.564	.658	.601	.270	1.000				
X4	-.162	-.009	-.729	-.554	-.669	-.115	1.000			
Y1	.668	.755	.056	-.263	.490	-.670	-.518	1.000		
Y2	.963	.226	-.329	-.460	.216	-.717	-.375	.729	1.000	1.000

Table 4.16 T – Test Result

Variable	**R**	**t value**	**p Value**	**Correlation**
X1	.963	6.21	0.0084184	Significant
X21	.226	0.40	0.7149526	non-significant
X22	-.329	-0.60	0.5890283	non-significant
X23	-.460	-0.90	0.4360640	non-significant
X24	.216	0.38	0.7277219	non-significant
X3	-.717	-1.78	0.1732747	non-significant
X4	-.375	-0.70	0.5338964	non-significant

Based on correlation matrix, it was found that the strongest correlations are between variables Y2 and X1. It implies that type of project has a positively and strong relationship with waste index, as shown in correlation value (r) of 0.963 which is almost equal to 1. Based on the assessments featured in this study and scoring category of Y2 (type of building) independent variables, it seems that institutional building would likely produce the least waste index. While residential building would produces the highest waste index.

Moderate to strong inter-variables relationships were also found in numerous occasions (Table 4.15). For instance, positive correlation between variables: X21 (rebar wastage) and Y1 (construction method); X22 (concrete wastage) and X3 (CFI); X23 (timber wastage) and X3 (CFI). This signifies that CFI value tends to increase as concrete and timber wastage increase. Moderate to strong negative correlations were also found between the following variables, such as:

- X3 and Y1 (CFI and Extent of IBS)
- X3 and Y2 (CFI and Type of Project)
- X4 and Y1 (EVR and Extent of IBS)

This also suggests that type of project and construction method play a major role in determining CFI and EVR values. Residential project with higher extent of IBS usages tends to produces the least CFI and EVR, which means less impact. Meanwhile, the weakest relationship were found in variable X4 (EVR) and X21 (rebar wastage), with correlation value (r) of - 0.09 which is close to zero. From Table 4.16, T- Test result shows the significance of correlation between variables Y2 and X1 (type of project and waste index), with correlation value (r) of 0.963. Moreover, there is also a considerably significant negative correlation between type of project and CFI, which denote less CFI value for residential project compared to institutional or commercial projects.

4.6 Assessments Summary

Overall analysis and comparison for the entire assessment outcomes was made to extract holistic overview and correlations between each assessment. This can be summarized in Table 4.17 as shown in the following page.

Based on assessment summary shown in Table 4.17, it can be highlighted that Project D can be considered as the best in terms of overall evaluations consist of extent of wastage and impact assessments especially for wastage CFI outcome, even though it has the highest waste index value. This is due to extensive use of IBS system. Contrary, Project A demonstrates that low waste index value does not reflect the overall level of sustainability as proven by high wastage levels and very high CFI index. Meanwhile, Project B and Project E, which are quite similar in terms of GFA/size, express rather averaged performances for all indices. Overall, wastage assessments from projects studied showed that the outcomes are highly contrasted. It reflects lack of benchmarks and standard practice among players.

This has shown that smaller-sized and low budget projects like institutional building are likely to generate less waste index. However, this outcome would not necessarily reflect the rest of wastage assessments. Wastage level for major materials in some projects may reach up to 10 %. The outcome is highly determined by waste management practice and method of construction. Baseline values among Malaysian contractors are yet to achieve the standard benchmark of 4 – 5 % wastage level as suggested by literatures. Thus, waste index alone does not reflect the overall picture in terms of sustainability of a building project.

Table 4.17 Assessments Summary for Construction Waste Generation from Chosen Sites in Klang Valley

Project	**A**	**B**	**C**	**D**	**E**
Type of building	Low Rise Institutional & Office, 4 storey	High Rise Institutional & Office, 12 storey	Low-Rise Commercial, 4 storey	High-End & High Rise Residential (Condominium)	Low Rise Institutional, 6 storey
Method of Construction	Conventional (plywood)	Semi-IBS (f.work system for columns & slabs, conventional for the rest)	Minor IBS (Mostly conventional, small portion using f.work system)	IBS-composite (precast panels and f.work system for slabs)	Conventional
Project Value/Cost (RM)	63,500,000.00	37,033,274.60	152,000,000.00	331,450,000.00	31,350,600.71
GFA (m^2)	17,000	15,800	143,600	123,002	15,000
Waste index (m^3/m^2)	**0.0339**	**0.0488**	**0.1087**	**0.1497**	**0.06804**
Wastage Level	**Rebar 5.15%, concrete 10.54 %, timber 100%, bricks & blocks 5.19%, plaster 8.03%, tiles 8.00%**	**Rebar 10.34%, concrete 10.20%, timber 100%, bricks 4.87%, cement 3.36%, tiles 3.20%**	**Rebar 5.71%, concrete 5.26%, timber 100%, bricks & blocks 3.63%**	**Rebar 9.63%, concrete 4.41%, bricks 5.06%, blocks 5.23%, cement 1.59%**	**Rebar 7.69%, concrete 1.01%, timber 9.77%, bricks & blocks 3.45%, plaster 8.09%, tiles 7.17%**
CFI (kg CO_2/ m^2)	**52.69**	**26.25**	**17.93**	**6.74**	**21.60**
EVR (x 100)	**2.4409496**	**2.7065859**	**5.5391496**	**1.9456631**	**2.8040576**
Evaluation	**Low Waste Index; High Wastage Levels; High CFI**	**Low Waste Index; High Wastage Levels**	**High Waste Index; Low CFI; High EVR**	**High Waste Index; Low Wastage; Low CFI/EVR**	**Low Waste Index**

Benchmark for CFI from construction waste in Malaysia shall be approximately 21 – 26 kg CO_2/m^2 for typical conventional projects and it shall be fairly less, up to 7 kg CO_2/m^2 for projects implementing full IBS system. This is comparably similar to finding reported by Kim et al (2006), which is 21.02 kg CO_2/m^2 of GFA for conventional high-rise residential project in Suwon, Korea. CFI values for waste generation in Malaysian construction industry are still extremely contrasted. Project A has extremely high CFI value due to poor environmental practice, including waste burial; open burning; and illegal dumping. Project D, as proven in CFI assessment, has the lowest carbon emission due to extensive use of prefabricated structural elements which lead to almost zero-waste generation for timber and steel.

Wastage CFI results were not necessarily aligned with waste index and they were heavily determined by the method of construction, also site quality control and waste management practice as reflected by wastage level outcomes. Correlation analysis suggests that CFI value is strongly determined by type of building and construction method. One of the reason waste index results were not proportional to wastage CFI results are because waste index quantification is based on the volume of construction debris generated. Meanwhile, one of the bases for carbon footprint estimation is associated with production processes which included in one of the life cycle of these products.

Wastage EVR benchmark for Malaysian construction industry shall lies around 0.0024 – 0.0028 for typical multi-storey projects applying conventional and/or partial semi-IBS, and shall be considerably less, by up to 0.0014 for projects utilizing full IBS system or projects with exceptionally good waste management awareness and practice.

Similar to CFI, EVR results are derived from wastage levels results. Thus, their outcomes shall be greatly determined by wastage levels for each specified materials. Also parallel to wastage CFI assessment, it seems that construction method, waste management, and building design play a major role in wastage EVR outcomes. Correlation analysis suggests that EVR value is greatly determined by type of building and extent of IBS usage.

Waste index is highly determined by size and scale of project. Nevertheless, waste index alone would not represent the overall performance of waste management practice, extent of wastage, and associated impacts of construction project. Thus, waste index outcome shall not be taken as the sole criteria for wastage evaluation alone. Wastage level, wastage CFI, and wastage EVR shall be also taken into account as part of criteria for sustainability of construction projects.

From the summary, it can be concluded that waste index value poses a statistically significant positive correlation with type of project. Low budget institutional project shall likely generate less waste index. Wastage level results showed rather proportional trends towards CFI and EVR outcomes. Correlation analysis also suggests that type of project and extent of IBS usage are crucial in determining CFI and EVR values. Residential and fully IBS project are proven to be the most sustainable, in terms of CFI and EVR values. Construction adopting full IBS system shall deliver faster completion, better quality and material control for concrete structure, thus producing a lot less “big three” waste (almost zero timber wastage), consequently far less financial loss (low wastage EVR result) as consequences of waste produced.

It is revealed that the consequences of construction waste generation are worse than perceived, especially its impact on environment. Result from these assessments showed that waste index, wastage level, wastage CFI, and wastage EVR figures in Malaysia are highly varying. This shows lack of benchmarking and standardized practices among players. Thus, benchmark level for these tools shall be established and reached to achieve more sustainable construction industry.

It is noteworthy to highlight that most waste produced is originated from temporary formwork, concreting, and other wet trades which involves “big three” materials. Therefore, zero-waste approach for “big three” materials should be the ultimate goal. Full and composite IBS system is recognized as the most effective measures which can achieve that target. In conventional system, no matter how good the waste management and awareness is, it still produce unavoidable waste due to the nature of works. Semi-IBS (metal formwork system) system also regarded as positive measure, but not as effective as full-IBS.

CHAPTER 5

DISCUSSION

5.1 Extent of Waste Generation

Extent of wastage which includes waste index and wastage level, have been previously discussed in Chapter 3. From the result presented in Chapter 4, it can be concluded that type of building, size of project, and site management are the main factors that contribute to construction waste generation as stated by previous studies (Gavilan and Bernold, 1994; Faniran and Caban, 1998; Ofori and Ekanayake, 2000a, 2000b; Poon, 2001b; Poon and Jaillon, 2004; Tam *et al.*, 2008). High-end buildings with aesthetic and sophisticated facades and design, regardless of the type of building, usually produce significantly higher quantity of waste. For these types of projects, contractors tend to commit errors particularly in regards to design issues, such as excessive material ordering, hacking of structure due to design error or last minute design changes as previously reported (Faniran and Caban, 1998; Dainty and Booke, 2004; Ofori and Ekanayake, 2000). Also, contractors tend to produce more waste due to more detailed and fine finishing.

Contrary to findings reported by Poon in Hong Kong (Poon *et al.*, 2001b; Poon *et al.*, 2004; Poon and Jaillon, 2009), constructions employing IBS system in Malaysia did not perform as expected, in terms of waste index. According to a number of construction personnel in charge, the main consideration for clients choosing IBS method is faster completion time. Projects C&D are the largest projects in this study, but project E has lower waste index due to low-rise structure, even though project C was the largest project featured in this study (143,600 m^2 of GFA). High-rise buildings such as project D produces more waste due to more extensive structural and concreting activities compared to low-rise buildings (Project A, C, and E).

As shown in Figure 4.4 previously, significant importance/value from the outcomes of objective (i) (refer to Sub-Chapter 1.4) in this study is the establishment of current benchmark for construction waste generation rates in Malaysia, specifically described in waste index term. Thus, the current status of baseline values for construction waste generation rates in Malaysia, taking account various types of building, in comparison with previous literatures reported from other countries are highlighted in Table 5.1, below.

Table 5.1 Benchmark of Waste Generation Rates in Various Countries

Country	Public residential (m^3/m^2)	Private residential (m^3/m^2)	Commercial (m^3/m^2)	Institutional (m^3/m^2)
Hong Kong (Poon *et al.*, 2001b)	0.175	0.250	0.200	N/A
U.S (Franklin Associates, 1998)	0.214	N/A	0.190	N/A
Spain (Solis-Guzman *et al.*, 2009)	0.308	N/A	N/A	N/A
Thailand (Gheewala and Kofoworola, 2009)	0.214	N/A	0.190	N/A
Malaysia	**0.0387 – 0.0519**	**0.1400 – 0.1500**	**0.1000 – 0.1500**	**0.0399 – 0.0680**

As outlined in Sub-Chapter 4.2, low rise residential, educational and governmental/institutional offices have the lowest waste indices due to their straightforward, symmetrical, and aesthetically conservative design. The formers are basically considered as low-end/low cost projects. Commercial, high-end office, and high-end residential shall generate the highest waste indices, respectively. This is contributed heavily by their unsymmetrical and aesthetically-pleasing design which relatively more complicated to construct. In this case, hacking due to design errors is frequently occurred. Thus, high-end projects consume more materials and wasted more.

From corporate management system point of view, it was found that there were no correlations between ISO14001-certified contractors with non-ISO14001-certified contractors on waste minimization performance. Contractors which adopted proper Waste Management Plan (WMP), and provisions on material storage and handling, as practiced on Project B, C, and D (Table 5.2) perform better in terms of wastage levels which was similar to previous findings reported (Poon *et al.*, 2004). This suggested that Environmental Management System (EMS) credential would not reflect contractors' environmental and waste management awareness. Most contractors claimed that adopting ISO 14001 served as compliance to governmental regulations and requirements. EMS is a very broad issue that mostly covers compliances standards. Construction waste generation and its associated impacts are very specific issues which require its own dedicated guidelines. WMP is an example of such guidelines (Poon *et al.*, 2004). Contractors should develop their own specific WMP, tailored to be applicable for each individual project. WMP shall cover the entire scope of waste generation from source until recycling and disposal. Tam (2008) stated that implementing WMP requires large investment in early stage of the project. Lack of top management support and commitment, lack of empirical experience, low incentives, and cost are the main difficulties in implementing successful WMP (Tam, 2008).

As seen on Table 5.2 below, Project C and D adopted WMP and result from assessments indicate good performance as seen on wastage level and CFI indices. WMP is likely to deal with waste issue thoroughly. Interviews with construction personnel revealed that improper handling and storage, lack of supervision, and poor workmanship are frequent common causes of waste generation. WMP also encourages reuse and recycling program to be implemented.

Table 5.2 Sources of Waste and Contractors' Credentials

Project	ISO14001	WMP	Material Handling & Storage SOP	Sources of waste	Major Material(s)
A	No	No	No	human error (workers' skills, poor handling); design (hacking due to design error); cut-offs; overordering, wet trades	Concrete, timber, plaster, tiles
B	No	Yes	No	human error (workers' skills, poor handling); design (hacking due to design error); cut-offs (unavoidable, especially rebars), overordering	Rebar, concrete, timber
C	Yes	Yes	Yes	Size of project; human error (workers' skills, poor handling; design (hacking due to design error); cut-offs	Rebar, timber, concrete
D	Yes	Yes	Yes	Size of project; human error (workers' skills, poor handling), technical problems, cut-offs	Especially rebar
E	No	No	No	Handling/operation, cut-offs, design error	Timber, rebar, plaster/finishing

From projects survey and interview sessions, steel reinforcement bar and other metals such as scaffolding and ceiling brackets are the only materials that worth to be salvaged for recycling purposes. Timber is usually reusable up to four times before eventually disposed off. Most contractors have already practiced this.

Project A, which did not adopt any WMP or any similar provision, surprisingly performed well in terms of waste generation. This was a rare exception which is mainly due to practice of open burning (especially timber and packaging waste) and illegal dumping, including concrete waste burial especially from piling. This was also practiced on Project B. While these practices may reduce the actual amount of waste to be disposed off at landfills and save considerable cost on disposal trips, they would pose greater impacts on environment.

Tam *et al.* (2008) found that effective actions to improve waste management include:

- Enforcement of legislation;
- Conducting training and education;
- Involving environmental consideration in design stage;
- Involving environmental consideration in tendering reports;
- On-site management systems;
- Improved communication.

Major sources of waste generation as highlighted on Table 5.2 suggest that poor handling due to human errors, cut-offs, and design errors were the most common causes. This had been discussed extensively in previous studies (Gavilan and Bernold, 1994; Faniran & Caban, 1998; Ofori & Ekanayake, 2000a, 2000b; Poon *et al.*, 2001b; Poon and Jaillon, 2004; Tam *et al.*, 2008).

Material wastage level is the main indicator for this issue. Project C and D possessed Material Handling & Storage Plan and performed well in wastage level and wastage CFI. Material Handling & Storage Plan will incisively minimize wastage due to these common and frequent avoidable causes (improper handling and storage).This is in line with material control philosophy suggested by Poon and Jaillon (2004).

Thus, it can be concluded that waste management-related issues are contributed to impacts associated with construction waste. Smaller-sized and low budget projects such as institutional building shall likely generate less waste index. In general, waste index and wastage level figures in Malaysian construction industry are highly varying. Result shows that construction waste generation rate benchmarks in Malaysia are still not up to mark. Wastage level for major materials in some projects may reach up to 10%. Baseline values among Malaysian contractors are yet to achieve the standard benchmark of 4 – 5% wastage level as suggested by previous studies (Jalali, 2006; Poon *et al.*, 2001b; Poon and Jaillon, 2009). Currently, there is still relatively lack of waste minimization awareness among construction players in Malaysia as reflected by poor waste record-keeping, lack of waste sorting and recycling practice, low usage of IBS systems, and lack of supports from top management, clients, and authorities. For Malaysian context, extent of wastage benchmarking for the purpose of waste minimization program can be described in the following illustration, as shown in Figure 5.1 below.

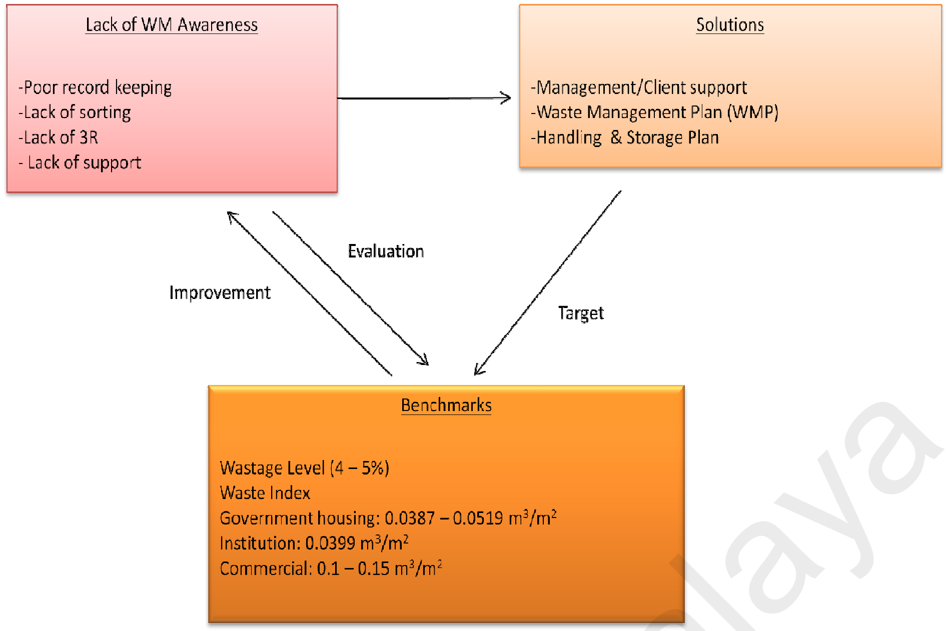


Figure 5.1 Benchmarking of Extent of Wastage for Waste Minimization in Malaysian Context

As outlined in Figure 5.1, problems associated with construction waste generation or lack of waste management awareness, are highlighted based on the result of this study. Material Handling and Storage Plan, Waste Management Plan (WMP), and general site management and practice, as identified and recommended by other studies, are reliable solutions for excessive waste generation. Meanwhile, benchmarks accomplished from relevant studies and assessments can be employed as basis for evaluation as these benchmarks represent baseline figures for Malaysian construction industry. Top management shall strive to achieve target benchmarks as part of corporate social responsibility and to improve contractors' reputation. Supports and commitment from top management and client are essentials for improvement as demonstrated by implementation of WMP (Tam, 2008).

5.2 Carbon Footprint Index (CFI) Assessment on Wastage

CFI on wastage is governed by wastage level calculation and has been previously discussed in Chapter 3. GHG protocol (ISO14040, 2006) classifies carbon emissions based on the level of control. The grouping of emission sources is based on the level of control within a business include:

- Scope 1– Direct carbon dioxide emission that results from business controls activities, such as from combustion of fuels on the business premises
- Scope 2– Emission from the use of electricity
- Scope 3– Indirect carbon dioxide emission that results from activities that the business perform but do not have full control over, such asproduction or purchase of raw materials and their delivery.

In this context, Carbon Footprint Index is categorized under 'Scope 3' emission source group.

Based on result of this objective, benchmark for CFI from construction waste in Malaysia shall be approximately 21 – 26 kg CO_2/m^2 for typical conventional projects and it shall be fairly less, up to 7kg $CO_2/m^2$for projects implementing full IBS system. This is comparably similar to finding reported by Kim *et al.* (2006), which is 21.02 kg CO_2/m^2 of GFA for conventional high-rise residential project in Suwon, Korea. Kim *et al.* (2006) concluded that steel bars are the biggest contributor of carbon emission (62%) based on material, while concreting work is the most dominant contributor (74%) based on type of activity, due to large quantity of construction waste generated.

Similar to waste index, CFI values for waste generation in Malaysian construction industry were extremely vary and contrast. Project A has extremely high CFI value due to poor environmental practice. Project D, as proven in CFI assessment, has the lowest carbon emission due to extensive use of prefabricated structural elements which lead to almost zero-waste generation for timber and reinforcement steel. Thus, these findings shall emphasize that construction waste carbon footprint benchmarking is crucial in determining the current status of global warming impact resulted by construction waste for Malaysian context.

As highlighted in Chapter 4.3, wastage CFI results were not necessarily aligned with waste index and they were heavily determined by the method of construction, also site quality control and waste management practice as reflected by wastage level outcomes. Correlation analysis highlighted in Chapter 4.5 which supports the findings suggests that CFI value is strongly determined by type of building and construction method. One of the reason waste index results were not proportional to wastage CFI results are because waste index quantification is based on the actual volume of construction debris disposed off. Meanwhile, one of the bases for carbon footprint estimation is associated production processes which included in one of the life cycle of these products. For instance, comparisons between wood products and metal products (such as reinforcing bars) witness the energy required to produce metal products is significantly higher than the energy needed to produce wood products in an equal volume. In other words, although metal-based wastage has a relatively smaller volume than timber wastage, but its contribution to carbon footprint emitted is quite enormous, as seen in Table 5.3.

Nevertheless, "big three" materials, i.e. concrete, timber, and reinforcement steels, encompass the highest global warming potential (Idemat, 2010 and Ecoinvent, 2010). They are also used extensively in construction and make up significant portion of waste quantity. From Table 5.3, it can be concluded that "big three" wastage pose the largest portion for potential GHG emissions which similar to findings concluded by Zabalza-Bribián *et al.* (2011).

From assessment results highlighted in Chapter 4, based on construction method, carbon emission contributed from timber and rebars shall be the varying factor. For project utilizing 100% portion of IBS system such as Project D, carbon footprint contributed from timber and rebars only constituted small portion of total carbon emission. Most of carbon footprint for projects utilizing 100% IBS would originated from concrete wastage. This composition would be entirely different than that of conventional projects.

For conventional projects (0 – 20% of IBS utilization), larger portion of total carbon footprint shall be generated from rebars and timber. Project utilizing some portion of IBS utilization would not be significantly different from conventional projects as other factors such as type of building and waste management also contribute to CFI.

Table 5.3 Contribution of Each Waste Material on Carbon Footprint for Chosen Projects

Material	Percentage of Total Carbon Footprint (%)				
	Project A	Project B	Project C	Project D	Project E
Concrete	20.85	40.57	28.03	75.89	5.44
Timber	21.42	19.86	42.25	11.04	3.39
Reinforcement Steel	8.07	29.02	26.79	0.15	29.47
Bricks & Blocks	5.86	0.11	2.92	6.12	5.11

Types of materials that significantly contribute to greenhouse gases emissions are manufactured materials which consume large amount of fossil energy. Zabalza-Bribián *et al.* (2011) pointed out that the amount of energy invested in manufacturing some specific materials for every one square meter (consider as gross floor area) in a standard building equals to the amount of energy extracted from the combustion of more than 150 Liters of petrol. Each square meter of built construction contributes to approximately 0.5 tonnes of carbon dioxide emission, which is vary depending on the building design, only accounting for the impact associated with these materials and not including additional emission from the use of heavy equipment and transportation (delivery). The relative contribution from each type of building material used to CO_2 emissions associated with a square meter of building in a Spanish standard block of flats can be seen in Figure 5.2. The high impact of commonly used materials such as steel, cement and ceramics is notable (Zabalza-Bribián *et al.*, 2011).

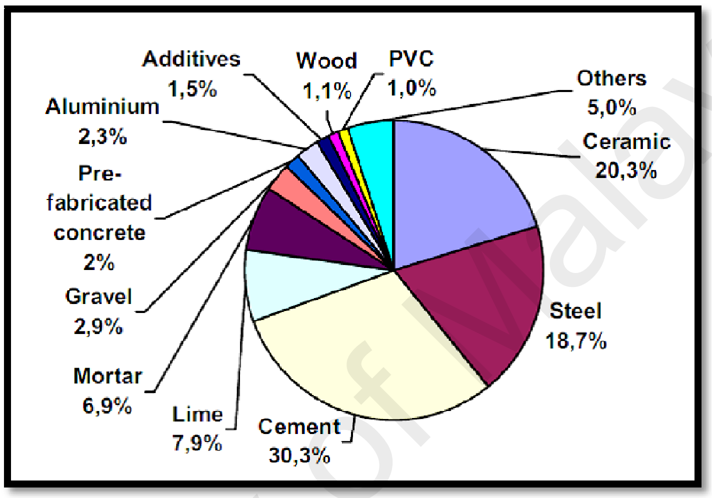


Figure 5.2 Contribution of CO_2Emission Associated with the Manufacture of the Materials Required for Construction of 1 m^2 GFA (Zabalza-Bribián et al., 2011)

Selection and usage of low GWP products, especially for major materials are preferred, which can also help reduce total carbon emissions. For example, below are some LCA results for several types of alternative bricks, tiles, and cements from literatures (Table 5.4 and Table 5.5).

Table 5.4 LCA Results for Several Types of Bricks and Tiles (Source: Zabalza-Bribián *et al.*, 2011)

Building Product	Global Warming Potential(kg CO_2-Eq/kg)
Ordinary brick	0.271
Sand-lime brick	0.120
Ceramic tile	0.857
Quarry tile	0.290

Building Product	Global Warming Potential(kg CO_2-Eq/kg)
Ceramic roof tile	0.406
Concrete roof tile	0.270
Fibre cement roof slate	1.392

Table 5.5 LCA Results for Cement, Concrete, and Reinforcing Steel (Source: Humphreys and Mahasenan, 2002).

Building Product	Global Warming Potential (kg CO_2-Eq/kg)
Cement	0.819
Cement mortar	0.241
Reinforced concrete	0.179
Concrete	0.137
Reinforcing steel	1.526

Based on interview sessions conducted during data collection process, most contractors agreed that better supervision is very crucial to ensure quality of works and avoid design and human errors which will lead to waste generation. The authors were also agreed that proper material storing/handling, intelligent and cut-to-size ordering are required for efficient use of materials and prevent over-ordering and left-over cuttings which is one of the common causes of wastage. These occasions occurs extremely frequent for “big-three” materials, especially during concreting phase and other structural works.

Based on recent studies and global warming potential for common construction materials indicated in Figure 5.2, it is clear that concrete reinforcement steels should be used sparingly and efficiently. Wastage CFI result in this study showed that the use of prefabricated elements is considered as effective measure because it significantly reduce the use and wastage of these materials (i.e high timber wastage and concrete spillage due to cast-in-situ formwork; plaster and concrete spillage due to typical wet trades). This finding shall also agree with studies reported frequently by Poon *et al.* (2001b; 2003; 2004; 2005; 2009) and Tam *et al.* (2008). Statistical analysis which supports the findings also suggests that CFI value is strongly determined by type of building and extent of IBS usage.

Zero-waste approach for "big-three" materials can significantly mitigate the potential environmental impacts caused by construction activities. Environmental impact due to waste generation shall be reduced since design stage of construction, rather than focusing on material control or recycling during end-of-pipeline stage of construction (Keys *et al.*, 2000; Poon *et al.*, 2009). "Sustainable development" should be listed at the top of novel waste management hierarchy, above waste prevention, as suggested by Keys *et al.* (2000) and "green building design" should be the vehicle to achieve that (Poon and Jaillon, 2009). Therefore, IBS system can modernize the construction industry to achieve enhanced quality, safety, and sustainability, as demonstrated by manufacturing industry nowadays.

For Malaysian context, benefits and application of CFI on wastage benchmarking can be illustrated in Figure 5.3, below. Based on result shown in Chapter 4.3 on CFI, conventional cast-in-situ concreting is considered as the main source of soaring carbon emission as consequences of massive construction waste generation, which potentially contributes to global warming impact. This activity is considered as the pillar and key element of conventional construction which will lead to excessive use and wastage of "big three" materials (concrete, timber, and reinforcement steel). Unavoidable sources of wastage (spillage and cut-offs), poor waste management and material handling are also contributing factors.

CFI benchmarking can be regarded as evaluation tool to assess the level of sustainability in construction project. As summarized before, full IBS project can produce only 7 kg CO_2/m^2, compared to typical conventional project which generate 21 – 26 kg CO_2/m^2 of GFA. This is similar to findings reported by Kim *et al*. (2006) in which typical conventional construction project produces about 21 kg CO_2/m^2 of GFA.

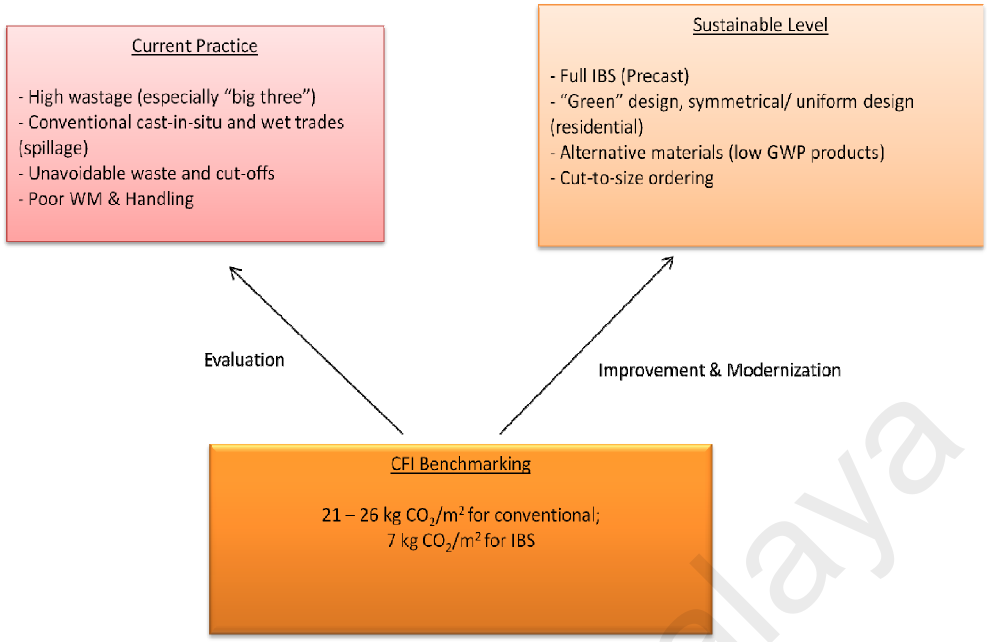


Figure 5.3 Benchmarking of CFI on Wastage for Malaysian Context

Result from CFI assessment is also in line with findings reported by Lachimpadi *et al.* (2012) which suggest that IBS system was found to be the most efficient construction method, with construction waste usage efficiency of up to 94%, compared to composite and conventional systems. Therefore, to achieve acceptable level of sustainability, full IBS construction method shall be considered since precast concrete elements would eliminate unnecessary wastage produced during structural phase of construction (Poon *et al.*, 2001b). Residential (including hotel) are the most suitable type of building to adopt IBS system due to their symmetrical and repeated design (Tam *et al.*, 2007a). Consuming alternative building materials can also help to reduce wastage CFI. Alternative or recycled products indicate low GWP materials (Zabalza-Bribián *et al.*, 2011).

Thus, benchmarks can be used to promote and modernized the Malaysian construction industry to adopt IBS system, precast technology in particular, and shift away from the traditional and resource-consuming conventional system (Lachimpadi *et al.*, 2012).

5.3 Eco-costs per Value Ratio (EVR) Assessment on Wastage

Similar to carbon footprint index (CFI) assessment, wastage level calculation will be the basis for most of eco-costs evaluation. As previously discussed in Chapter 3, Eco-costs considered in this study include:

1. Landfilling Cost
2. Unit Cost and Delivery Cost
3. Labor Cost
4. Total Disposal Trip Cost

From the finding, wastage EVR benchmark for Malaysian construction industry shall lies around 0.0024 – 0.0028 for typical multi-storey projects applying conventional and/or partial semi-IBS, and shall be considerably less, by up to 0.0014 for projects utilizing full IBS system and projects with exceptionally good waste management awareness and practice.

Similar to CFI, EVR results are derived from wastage levels results. Their outcomes shall be greatly determined by wastage levels for each specified materials. Therefore, waste management-related issues are also considered as contributing factors. More wastage produced (such as unavoidable spillage due to concreting activities) will consequently result in increased use of resources (labor manpower for housekeeping and disposal trips) for waste management purposes. Also parallel to wastage CFI assessment, it seems that construction method, waste management, and building design play a major role in wastage EVR outcomes. Correlation analysis highlighted in Chapter 4.5 which supports the findings suggests that EVR value is greatly determined by type of building and extent of IBS usage. This is similar to CFI.

Votglander *et al.* (2006) suggested that wastage EVR index is a link between the value chain and product chain and so for two projects with the same waste index and moreover same eco-costs, if the two have different values then they will have different EVR indices, where the greater the value the lower the EVR index. Furthermore low waste index and eco-cost does not implies low EVR, because if the value of a project is also low then the EVR will be as high as other project with high eco-cost but with higher perceived value.

Project D performed tremendously in wastage EVR result, composite precast concrete elements and metal formwork system which can substantially reduce the usage of “big three materials”, compared to cast-in-situ concreting by employing timber formwork. Moreover, residential type of building which usually has uniform and repeated design strongly permit the application of IBS system. This is aligned with correlation analysis conducted in Chapter 4.5 in which EVR was highly determined by type of building. Since formwork may account up to 60 % of the cost of concrete construction, it is essential that the formwork plan can be carefully developed and evaluated (Nunnally, 2007). Lower formwork cost will result from repetitive use of forms. Multiple-use forms can be established by prefabricated formwork system.

Full IBS system is the next level of prefabricated formwork system. One of the most widely-used IBS elements is precast concrete. According to Nunnally (2007), there are a number of advantages obtained by removing conventional concrete casting activities such as formwork, especially environmental benefits. Since standard shapes are commonly used, the repetitive use of formwork permits forms to be of high quality at a low cost per unit. Due to controlled environment and procedures, concrete quality control is also superior to that of cast in-situ concrete (Nunnally, 2007). Upon arrival at site, precast concrete may be erected more rapidly than conventional cast in-situ components. Thus, it can be concluded that wastage EVR result shall be improved if less "big three" consumption and wastage was generated. This is similar to findings reported by Poon *et al.* (2001b, 2004, 2005, and 2009) which suggested that timber and cast-in-situ concreting are major contributors of construction debris.

Thorough analysis on wastage EVR methodology shall implies that wastage EVR is actually the percentage of cumulative costs associated with waste generation out of total project cost. During interview sessions and data collection phase, most Project Managers or QSs claimed that the cost spent for waste management is almost negligible, which were less than 1% of total contract sum. However, based on the findings, wastage EVR assessment proofed that actual direct and indirect financial losses due to wastage produced were much more costly than the figure claimed.

According to a study conducted by De Jonge (2005), EVR value for typical office building could reach up to 37% of total project sum, for scope covering overall construction phase which ranging from the superstructure to finishing stage. Therefore, design stage is very crucial for planning and decision-making in developing sustainable project as indicated by EVR assessment. The eco-costs for construction site waste covered in this study are subset of the total eco-costs of a construction project (Yahya and Boussabine, 2006). EVR can be regarded as one of the indicators for sustainability level of construction projects. Low EVR figure signifies that a project is fit-for-use in a future sustainable society, while high EVR figure suggests it may not fit in the future because the cost of delivering (construction) is higher than its actual value. The lower the EVR value, the better it is for society (Votglander *et al.*, 2001).

According to Votglander *et al.* (2006), there are several environmental strategies to improve or lower the EVR of a project, which include improvement of production process (in this case, the construction method) by using sustainable materials (which often lead to higher initial cost), to dedicate on "savings" (e.g. transportation and energy consumption), and improvement of the perceived value from the building aspect.

For Malaysian context, benefits and application of wastage EVR benchmarking can be illustrated in Figure 5.4, below.

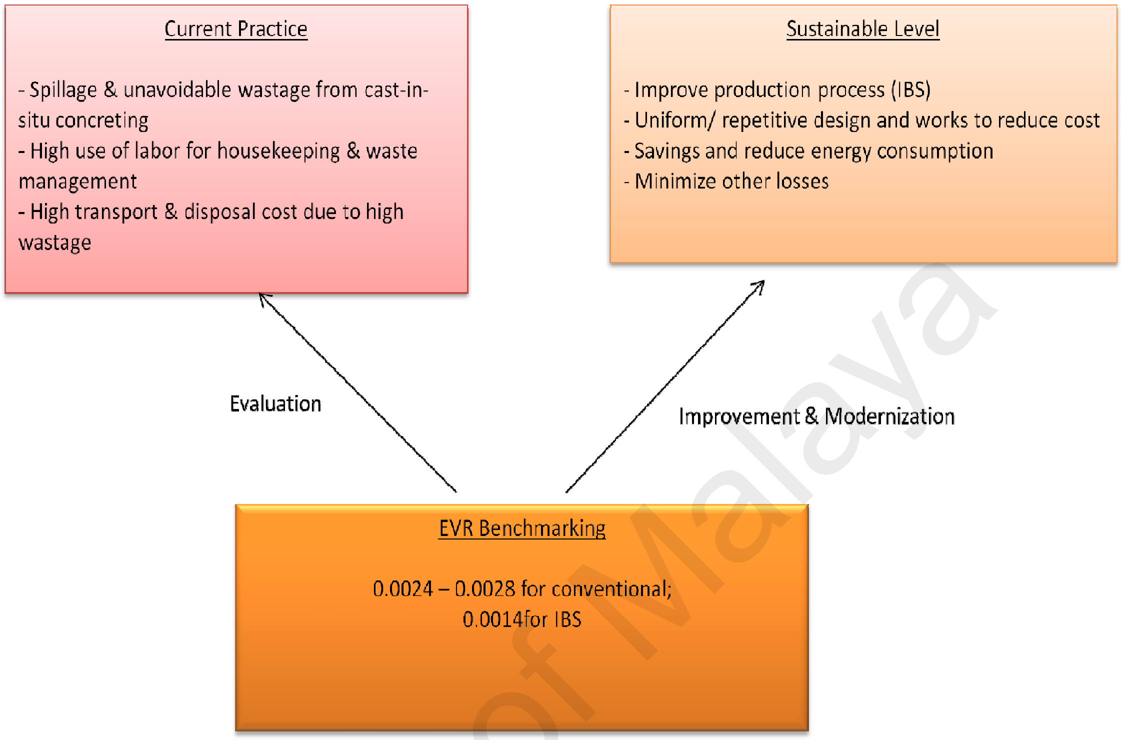


Figure 5.4 Benchmarking of Wastage EVR for Malaysian Context

From the result highlighted in Chapter 4, cast-in-situ conventional construction is the main cause of high wastage EVR value, is similar to CFI. This is because high extent of spillage and unavoidable wastage tend to reflect low productivity and would lead to considerable amount of investment in on-site waste management, including high degree of labor utilization for housekeeping and waste sorting, lorry trip cost, and disposal fee. EVR benchmarking would help to determine the baseline of sustainability level for typical construction projects in Malaysia. EVR is one of the indicators for sustainability in construction projects. Low EVR figure signifies that a project is "fit for use" in a future sustainable society (Votglander *et al.*, 2001).

To develop higher sustainability level, construction sector needs to improve production process, as practiced by manufacturing industry (Votglander *et al.* (2006).

This shall indicate the utilization of full IBS system. Design would also play a major role to determine the magnitude of environmental impact and risk that will be generated. These shall be the key factors to improve EVR figure and overall sustainability of construction project. Elements such as efficiency and productivity, in terms of energy consumption, labor usage are also contributing factors. In addition, dynamics and interrelationships simulations indicate that wastage reduction can be significantly maximized through higher landfilling charge (Yuan *et al.*, 2012). These findings also suggest that investment in waste management and major compliances or credentials have considerable impacts on reduced wastage level, which consequently resulted in lower EVR.

5.4 Overall Overview and Interpretation

From the result of this study, it is revealed that the consequences of construction waste generation are worse than perceived, especially its impact on environment. Problems associated with construction waste are not shortage of landfill areas due to large volume of debris disposal alone, but also resources depletion, massive GHGs emissions, inefficiency, and financial loss. Result from these assessments showed that waste index, wastage level, wastage CFI, and wastage EVR figures in Malaysia are highly vary and scattered. Thus, benchmarks level for these evaluation tools shall be established and met to achieve a more sustainable construction industry.

It is noteworthy to highlight that most waste produced is originated from temporary formwork and concreting, including considerable quantity from hacking due to errors, finishing works, and other wet trades which involves “big three” materials. Therefore, zero-waste approach for “big three” materials should be the ultimate goal for sustainability. Full and composite IBS system is recognized as the most effective measures which can achieve that target. In conventional system, no matter how good the waste management and awareness is, it still produce unavoidable waste due to the nature of works. Semi-IBS (metal formwork system) system also regarded as positive measure, but not as effective as this is still considered as cast-in-situ concrete casting, but without the use of timber.

Keys *et al.* (2000) proposed the term 'designing-out waste' in which the purpose is to develop waste minimization strategies through design approach, rather than 'end-of-pipeline' waste management. By redirecting the focus of waste minimization to the earliest stage of the projects, the greatest opportunities for waste minimization and recycling exist (Figure 5.5**)**. Osmani (2012) agreed with the concept and recognized the key role and responsibilities of architects in the construction industry, to strive in adopting 'Eco-effective' practices by implementing a holistic approach to design for waste minimization. According to Poon and Jaillon (2009), the benefits of waste minimization could be improved drastically if green and sustainable building designs were considered instead of focusing on construction process/on-site operation and material control. Keys *et al.* (2000) suggest long term approaches in designing out waste, such as: prefabrication; standardization; optimizing design live; allowing recycled materials in design; designing for ease of disassembly and recycle.

However, studies also indicate that a number of constraints, namely: lack of interest from clients; attitudes toward waste minimization; and training are all act as disincentives to a proactive and sustainable implementation of waste reduction strategies during design process (Osmani *et al.*, 2008). In addition, Osmani *et al.* (2008) also reported that most respondents in the conducted survey perceived 'legislation' and 'financial rewards' as the best incentives to promote waste minimization through design.

Figure 5.5 shows that current waste management hierarchy suggested by Keys *et al.* (2000) that covers more comprehensive issues that dealt with waste management.

This novel waste management philosophy shall make the most of every quantity of wastage, including on-site reuse & recovery, including off-site reuse and recovery such as salvaging after practicing waste prevention and reduction. ‘Sustainable Development’ refers to reducing waste and its impacts through design as also proposed by Poon *et al.* (2001b) as adapting “Low-Waste Building Technology”. “Low-Waste Building Technology” such as precast IBS system shall modernize the construction industry from traditional approaches that identical with lack of safety, dirty, and generate large quantity of waste (Poon *et al.*, 2001b). Sustainable development is the best approach in dealing with construction waste and associated impacts. This shall be considered as the ultimate goal. This philosophy shall be the basis in decision-making within contractors and for formulating policy and guidelines for Malaysian construction industry.

IBS system (fully precast elements or composite) can provide expected sustainability level by delivering improved Quality Control (as building elements are manufactured in highly supervised processes) and project completion speed, which lead to less emissions, less impacts, and minimized losses. Nevertheless, good environmental and “end-of-pipeline” waste management practice is still important. A combination of both is highly preferred.

Sustainable Development	**Best**
Prevention	
Reduction	
On-site reuse	
On-site recovery	
Off-site reuse	
Off-site recovery	
Landfill	**Worst**

Figure 5.5 Waste Management Hierarchies from “Designing-Out Waste Philosophy” (Source: Keys *et al.*, 2000)

Future development of IBS is also very important to highlight. In general, the most popular prefabrication implementation is mainly for structural elements (such as column, beam, wall, and slab) using formwork system (semi-prefabricated), and for internal finishing works (plastering, and tiling) using comprehensive prefabrication (Tam *et al.*, 2007b). From financial aspect, Tam *et al.* (2007b) also found that up to 87% of cost saving can be realized from wastage reduction for four major materials (concrete, reinforcement, plastering, and tiling). However, IBS can bring cost saving if these key factors are addressed: (1) fully mechanizing on heavy plants; (2) turning construction into assembling; and (3) using recycled materials for precast elements. In addition, these measures are likely to be implemented to stimulate prefabrication adoption.

Based on type of project, Tam *et al.* (2007a) reported that residential and hotel are the most suitable projects for IBS in order to reduce wastage due to their symmetrical and uniformity of design, and constant IBS demand for this type of building, as proven in Project D. Meanwhile, hospital and shopping malls, such as Project C, are perceived as least suitable due to small numbers of related projects to support IBS at a competitive price (Tam *et al.*, 2007a).Findings confirmed by correlation analysis highlighted in Chapter 4.5 suggest that environmental impacts generated are greatly determined by type of building and extent of IBS usage. Residential type of building which usually has uniform design strongly permit the application of IBS system, as demonstrated in Project D.

In order to promote the use of IBS, governmental ordinance is crucial, besides technical advancement and widespread of demands, especially from private clients. Among the popularly perceived government supports are: providing incentives such as floor area exemption or relaxation; promoting green building technology and its related certification (Poon and Jaillon, 2009). For instance, Singapore government has legislated 'buildability' rating system or Buildable Design Appraisal System (BDAS) whereby projects need to fulfill minimum buildable score before their development can be approved (Low and Choong, 2001a). High score can be achieved by greater use of prefabrication technology. According to Low and Choong (2001a), BDAS put emphasis on standardization, simplicity, and single integrated element which means, high buildability can lead to high productivity. Mandatory regulations can highly encourage the use of prefabrication in construction projects, particularly at the initial implementation stage (Tam *et al.*, 2007a).

Another issue that needs to be addressed is space restriction for storage and traffic congestion at worksite which can be lessened for improving the movement of precast concrete elements. According to Low and Choong (2001b), late delivery by precaster is the most frequent problem encountered by contractors. Hence, the Just in Time (JIT) philosophy, whereby heavy precast elements are expected to be manufactured and delivered just in time for installation and erection on site (Low and Choong, 2001a).

For Malaysian context, Badir *et al*. (2002) pointed out that to recommend the use of IBS, raw materials used have to be produced locally to overcome shortages as IBS in Malaysia are mainly originated from the US (25%), Australia (17%), and Germany (17%). For IBS implementation in Malaysia, Lim (2006) suggested that standardization of the material and sizing as well as quality control policy needs to be legislated so that it can govern the manufacturers and installer to produce high quality construction. Lim (2006) also suggested that there should be a sole agency that will look into the issues of legislation, training, R&D, and resources of IBS. Moreover, it is suggested to produce IBS system locally as IBS systems currently are mainly imported. Other barriers related to the implementation of IBS, as concluded from interview sessions, also parallel to findings reported by Haron *et al.* (2009), include:

- Cost and return investment;
- Lack of skilled manpower;
- Inconsistent policy, guidelines, and practice among the players involved;
- Inflexibility and incompatibility of components making precast components less competitive;
- Low quality unlike in developed countries;
- Lack of incentives and awareness from authorities;

With sufficient demand for IBS, major area of business related to IBS construction could be cultivated and expanded, such as: building product manufacturing, main supplier of building materials, and main contractors (Badir *et al.*, 2002). As the technology matures, more clients and contractors would likely to demand this method. And with the support of government action (such as providing incentives and stimulus), in the future, prefabrication will be the method of choice, not only to reduce waste, but also to reduce cost as well (Chiang *et al.*, 2006).

Bottom line, Tam *et al.* (2007c) pointed out that government support is vital as far as the authors' concern to revolutionize the industry towards sustainability. Countries like Hong Kong and Singapore have implemented intelligent policies in favor of IBS system such as GFA exemption (Poon *et al.*, 2009; Poon and Jaillon, 2009) and waste management such as disposal charge scheme, buildability rating, and C&D waste tracking system (Nitivattananon and Borongan, 2007). These are some good examples of government supports and initiatives.

From the people aspect itself, improvement could be driven by consumers/clients' attitude towards sustainable and "green" processes and products, the contractors by proposing green solutions to the market, and the authorities as policy-makers by focusing on green approaches towards the industry, such as providing incentives for green technologies/products. From these strategies, it seems that modernization of the construction processes, efficiency, legislations, and financial incentives or disincentives are the most reliable measure to improve the sustainability of Malaysian construction industry as concluded by Dainty (2004) and Osmani (2008). The main hindrances in implementing IBS in Malaysia are high-cost, low demand, inflexibility, fragmented stakeholders, inconsistent regulations/policies, and abundance of cheap foreign labors. Hence, all stakeholders, not only contractors, shall focus on "designing-out waste" which emphasize on IBS technology and standardization as suggested by Keys *et al.* (2000).

As for Malaysia, the future outlook for sustainable development in construction industry can be summarized as illustrated in Figure 5.6, below. From Figure 5.6, it can be highlighted that this illustration shall represent a model for long-term development and modernization in order to achieve sustainable development in Malaysian construction industry, particularly to promote IBS implementation.

This model shall provide an extensive emphasis and burden on Authorities. This implies how crucial the role of authority is for achieving a more sustainable construction industry. Authorities' roles are to formulate policy, guidelines and regulations, besides monitoring for all stake holders (clients, designers, contractors, and suppliers). To support high extent of IBS adaptation, one of the approaches is to revamp the current foreign labor policy. As reported by Lim (2006) and Haron *et al.* (2009), IBS adaptation in Malaysia is relatively low due to low utilization of local labors and abundance in cheap foreign labor (including illegal migrant labors), particularly from neighboring countries.

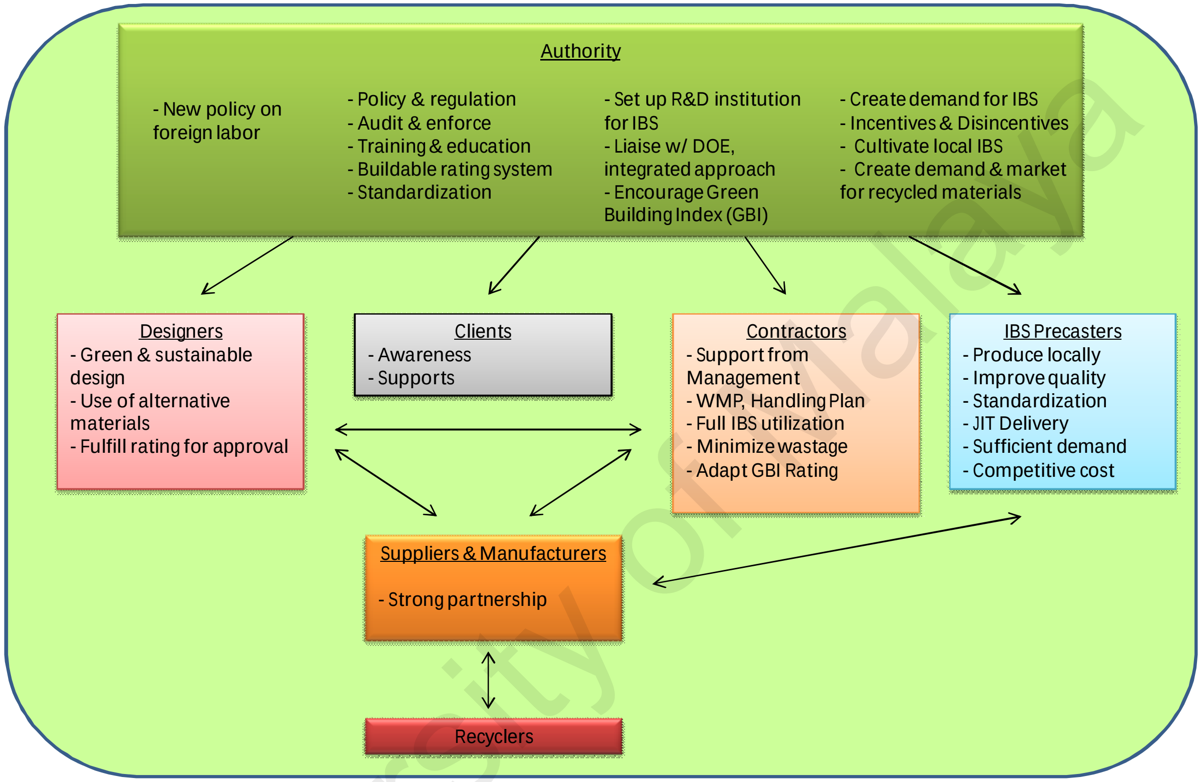


Figure 5.6 Future Outlooks for Sustainable Developments of Malaysian Construction Industry

Incentives and disincentives such as GFA relaxation and penalties/compounds for contractors shall also help to boost IBS implementation as repeatedly reported in a number of studies (Lim, 2006; Tam *et al.*, 2007c; Osmani *et al.*, 2008; Poon *et al.*, 2009; Poon and Jaillon, 2009). For example, the success of off-site waste sorting program in Hong Kong is mainly due to 'policy support' and 'good policy execution', including disincentives such as 'higher disposal charges' and 'implementation of trip-ticket system' (Lu and Yuan, 2012). Stringent monitoring and enforcement for contractors' sustainability level is another positive policy which based on current performance benchmarks such as waste index, CFI, and EVR. This shall ensure that contractors shall meet the standards imposed by the authority. Standardization, training, and education have been also mentioned repeatedly which had proven to make a considerable impact in IBS usage (Tam *et al.*, 2007a; Poon and Jaillon, 2009).

Buildable rating system is an interesting approach, introduced by Singaporean CIDB, in which designers are obligated to achieve minimum sustainability score prior authority's approval before execution of construction (Low and Choong, 2001a). This is a perfect example of 'designing-out' waste philosophy. Alternatively, such rating resembles the Malaysia's Green Building Index (GBI hereafter) rating system which had already been introduced in 2009 (Green Building Index, 2010). GBI-certified buildings mandate contractors to achieve certain GBI rating as minimum requirement which can be achieved by introducing "green" features and construction practices. GBI would serve as the "vehicle" to achieve sustainable building design which incorporates 'designing-out' waste philosophy, such as IBS implementation, other low-waste building design and technologies, including sound waste management plan, as parts of its requirements. Provisions to put more emphasize on reducing construction waste generation and its associated impacts are highly suggested, as currently the weighed score for "Material & Resources" under the GBI Assessment Criteria are only 11 out of

100 and 9 out of 100, for non-residential and residential constructions, respectively (Green Building Index, 2010).

Other measures such as setting up R&D institution for IBS; cultivating local IBS precasters; creating demand for IBS projects have been proposed (Lim, 2006; Haron *et al.*, 2009). Malaysian CIDB has recognized its benefits and has actively promoted the use of IBS in Malaysia, thus, improving the construction industry's environmental performance and commitment to sustainable development as outlined by the CIDB's Construction Industry Master Plan 2006–2015 for Malaysia (Lachimpadi *et al.*, 2012). The authority and government has an important role as a client in order to support the utilization of full IBS system for government's institution buildings as this will flourish the local IBS business development.

All stakeholders shall uphold strong partnership and communication in order to sustain high level of coordination and supports within construction industry value chain. This strong bonding will speed up the development of IBS implementation, including recycled materials in order to achieve more sustainable construction industry.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This final chapter highlights the conclusion from previous chapters. In addition, this chapter will also elaborate the implications of this study, the contribution of this study, and recommendations in order to achieve more sustainable Malaysian construction industry.

Construction waste poses serious environmental impacts. High demands of infrastructure and building projects considered as the main contributors for construction waste generation and its associated impacts in Malaysia. Malaysian construction industry needs to strive for the establishment of benchmark figures and strong database for national construction waste generation and its associated impacts. The objectives of this study include:

1. To identify the benchmark value for waste index
2. To identify the benchmark value for wastage level
3. To identify the benchmark value for carbon footprint index (CO_2 emissions)
4. To identify the benchmark value for eco-costs/value ratio (EVR)

These indices are regarded as indicators for extent of wastage and associated impact (global warming), and environmental burden prevention cost in Klang Valley. Five projects in Klang Valley had been selected for this study, which mainly include institutional, residential, and commercial building projects conducted by a wide range of contractors employing conventional and IBS systems. Major waste that generated at significant amount, such as concrete, timber, reinforcement bars, bricks & blocks, tiles, and plaster/mortars were taken into account. Only waste generated from construction activities at superstructure phase was considered. Data used for the study was collected in three ways: interview with key personnel, observational site visit, and reviews of project documentation.

Result from each evaluation and objective of study, including their outcomes, implications, and contributions are presented in the following sections, below.

6.2 Conclusion

Benchmark for waste index for chosen sites shall fall between 0.0339 - 0.1497 m^3/m^2. Benchmark wastage levels for each specified material should fall around an average of 5 – 6 % and up to as high as 10%, except for timber which eventually will be 100% disposed off for conventional projects. Low-end institutional projects shall be likely to generate less waste index due to small size and budget nature of the building.

Rather than by the method of construction, waste index are merely governed by the waste management practice performed by the contractor, design, and size of the respected project. The values tend to be less for small projects such as institutional or educational buildings. Wastage level would more likely to reflect the contractors' waste management awareness and overall productivity.

Benchmarks for wastage CFI shall range between 21 – 26 kg CO^2/m^2 for typical conventional projects and it shall be considerably less for projects employing extensively higher extent of IBS usage. CFI assessment for waste generated is governed by wastage level analysis for each specified material. Big three materials have the highest global warming potential (GWP) value.

Product and delivery cost/unit, cost of waste disposal, cost of land filling, and cost of labor for waste collecting were identified as eco-costs accounted in assessments.

Benchmarks for wastage EVR benchmarks shall fall between 0.0024 – 0.0028 for typical multi-storey projects and less for composite or full-extent IBS projects.

Construction method, waste management, and type of building play a major role in environmental impacts (CFI and EVR outcomes). Residential and fully IBS project are proven to be the most sustainable, in terms of CFI and EVR values. Wastage level results showed rather proportional trends towards CFI and EVR outcomes. Waste index outcome has significant positive correlation with type of project. Waste index reflects the actual debris transported to landfills. Low-end projects tend to generate less waste index due to minor size and cost of the building, but not necessarily produce lower impacts.

Therefore, based on the result of this study, the qualitative baseline of good sustainable building shall include design (simple, uniform shaped, compatible with low-waste and green features); IBS system (particularly precast concrete); dedicated WMP and Material Handling & Storage Plan. It is highly suggested that, prior to project execution, preliminary evaluation should be made to look into issues such as design, construction method, and contractor's compliances or credentials.

6.3 Implications of Study

To sum up, construction waste generation poses more severe impacts than it was generally perceived. This study unveils the construction waste issue from a different angle of perspectives instead of the general solid waste problems widely studied, reported, and published. By analyzing from overall and more holistic point of view, it is apparent that problems associated with construction waste are not just excessive debris disposed and shortage of landfills, but also resources depletion, massive carbon emissions, inefficiency, financial and other losses. Over-reliance on typical construction waste quantification techniques such as waste index approach shall be avoided due to lack of accuracy in assessing impact consequences as shown on the findings of this study. Project with low waste quantification outcome does not imply that it generate low environmental impacts as waste index is mostly influenced by the size and cost of the project. Residential projects employing high-extent of IBS are found to be the most sustainable. However, only small portion of demands are in favors for this type of project as they can be categorized as high-end (high-cost) projects.

6.4 Contributions of Study

Findings suggest that the entire tools featured in this study (waste index, wastage level, wastage carbon footprint index, and wastage eco-costs per value ratio) shall act as performance-based multi-indicators to assess overall sustainability of construction project as shown by wastage produced. Most previous studies usually focus this only on one aspect or tool, rather than attempting to tackle multiple issues caused by construction waste. The main purpose of these multi-indicators assessments featured in this study is not to prove which one is the most suitable, but to provide comprehensive and integrated evaluations for consequences and environmental impacts due to construction waste generation. Each assessment should complement each other and that waste generation shall be treated as an integral part of overall environmental performance or sustainability level and shall be considered as part of project's main objectives.

Result of this study illustrates that the baseline figures are highly contrast and scattered, which show inconsistency of sustainability level demonstrated among construction players. For that reason, benchmark figures shall be necessarily established by authorities and shall be achieved by construction players. Benchmarks are crucial to gain deep understanding of construction waste issue and to assess the current status of the industry while thriving to progressively reach achievable targets based on long-term goals. Policy-making and effectiveness of measures are launched or evaluated based on benchmarks accomplished. Finally, sustainable development shall be educated and socialized to all stakeholders in construction industry to reach the expected level.

6.5 Recommendations

6.5.1 For Contractors

Construction players shall put more emphasize on preventive-approach low-waste building design (uniform and simple design, suitable with IBS system), rather than focusing on sound waste management, such as reuse, recycling, and material control. Despite good waste management practice, construction works still generate unavoidable waste due to the nature of this industry. Recycling of construction waste is very difficult to implement because it involves on-site waste sorting and segregation which is very tedious and time-consuming process. Meanwhile, with an exception to steel reinforcement bars, construction waste usually exists as mixed and heterogeneous debris.

IBS system, or sometimes called prefabrication, and also known as the complete assembly construction, which is a construction system where components are manufactured at factories or off-site, transported and then assembled into a structure with minimum work, was concluded as the most effective measures to minimize extent of wastage and associated impacts/losses resulted from construction waste generation as proven in this study. But, implementation of IBS is highly constrained by lack of demand and high cost issue.

Benchmarks for sustainability shall be met and must be treated as integral part of project objectives. Waste Management Plan (WMP) shall also be established and put in order as complementary guidelines. ISO140001 certification seems not so useful in terms of mitigation of construction waste impacts.

6.5.2 For Authorities

Construction industry needs a breakthrough and modernization to achieve long term goal in sustainable development. Malaysian construction authorities, mainly CIDB and JKR shall provide their full support to achieve a more sustainable practice of industry, especially the implementation of low cost and applicable IBS system. IBS construction method is not new, but it is still very difficult to implement. Advantages, hindrances, and measures to improve IBS implementation have been repeatedly studied in many countries and should be useful references. Assessment tools, methodologies, and findings of this study shall benefit the authorities to develop and establish sustainable policies and guidelines such as:

- To set up stringent environmental requirements and legislation for construction waste generation based on established benchmarks.
- Provide financial disincentives such as: carbon tax, disposal charge scheme, severe penalty for illegal dumping, increase workers wage, limit the number of foreign labors, use of recycled aggregates, etc.
- Provide financial incentives in favor of IBS implementation, such as: GFA relaxation for IBS projects, financial support for local IBS precasters and manufacturers.
- Create market and infrastructures for IBS, improve quality of IBS manufacturers, standardization of IBS dimension and system.

6.6 Future Studies

Further studies include:

- Develop comprehensive database of benchmark figures for Malaysian construction industry

- Develop computerized and standardized tools that can be applied by construction players and authorities to assess sustainability benchmarks
- Further carbon footprint and eco-cost assessments which include construction phase or even the entire lifecycle of the building, not only construction waste generation
- Developing better and more sustainable and zero-waste building technologies

REFERENCES

Abdul Kadir, M.R., Lee, W.P., Jaafar, M.S., Sapuan, S.M., Ali, A.A.A. (2006). Construction performance comparison between conventional and IBS in Malaysia. *Structural Survey* ***24 (5)****, 412-424.*

Badir, Y.F., Abdul Kadir, M.R., Ali, A.A.A (1998). Theory of Classification of Badir-Razali Building System Classification. *Bulletin of Institution of Engineer, Malaysia, October 1998.*

Badir, Y.F., Abdul Kadir, M.R., Hashim, A.H. (2002). Industrialized Building Systems Construction in Malaysia. *Journal of Architectural Engineering* ***8(1)***.

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

Baldwin, A.N., Shen, L.Y., Poon, C.S., Austin, S.A., Wong, I. (2009). Designing-out waste in high-rise residential buildings: analysis of precasting methods and traditional construction. *Journal of Renewable Energy* ***34****, 2067- 2073*.

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

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

Begum, R.A., Pereira, J.J., Siwar, C., Jaafar, A.H. (2009b). Contractors' willingness to pay for improving cons waste management in Malaysia. *Malaysian Construction Research Journal* ***4 (1)***.

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

Bergsdal, H., Bohne, R.A., Brattebø, H. (2007). Projection of construction and demolition waste in Norway. *Journal of Industrial Ecology* ***11(3)****, 27-39*.

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

Brick Development Association. (2006). *A Sustainabilty Strategy for the Brick Industry*. Berkshire, UK, Brick Development Association.

Buchanan, A.H., Levine, S.B. (1999). Wood-Based Building Materials and Atmospheric Carbon Emissions. *Environmental Science and Policy* ***2,*** *427-437*.

Building and Construction Authority, Singapore (2004). *Buildable Solutions for High-Rise Residential Development*. Singapore: BCA Publishing.

Burgess, A.A., Brennan, D.J. (2001). Application of Life Cycle Assessment to Chemical Processes. *Chemical Engineering Science* ***56,*** *2589-2604*.

Chang, Y., Ries, R.J., and Wan, Y. (2010). The Embodied Energy and Environmental Emissions of Construction Projects in China: An Economic Input–Output LCA Model. *Energy Policy* ***38,*** *6597–6603*

Chiang, Y.H., Chan, E.H.W., Lok, L.K.L. (2006). Prefabrication and barriers to entry – a case study of public housing and institutional buildings in Hong Kong. *Habitat International* ***30****, 482 – 499.*

Cochran, K., Townsend, T., Reinhart, D., Heck, H. (2007). Estimation of regional building-related C&D debris generation and composition: case study for Florida, US. *Journal of Waste Management* ***27****, 921-931*.

Construction Industry Development Board. (2004). Retrieved from *http://www.cidb.gov.my/v6/?q=en/content/preceeding-papers.*

Construction Industry Development Board. (2009). Construction Opportunities in the 9th Malaysia Plan. Retrieved from *http://www.cidb.gov.my.*

Construction Industry Development Board. (2009). *Katalog IBS (Bagi Projek Bangunan IBS).* Kuala Lumpur: CIDB Publishing 1st Edition.

Construction Industry Development Board, Singapore (1997). *Guide to Precast Concrete and Prefabricated Reinforcement for Buildings.* Singapore: CIDB.

Choudhury, Amit.(2009). *Statistical Correlation*. Experiment Resources.

Coventry, S., Shorter, B., Kingsley, M. (2001). *Demonstrating Waste Minimization Benefits in Construction*. London: Construction Industry Research & Information Association (CIRIA), UK.

Curran, M.A., Notten, P. (2006). *Summary of Global Life Cycle Inventory Data Resources*. Task Force 1: Database Registry. SETAC/UNEP Life Cycle Initiative.

Dainty, A.R.J., Brooke, R.J. (2004). Towards improved construction waste minimization: a need for improved supply chain integration? *Structural Survey* ***22 (1)****, 20-29.*

De Jonge, Tim. (2005). *Cost Effectiveness of Sustainable Housing Investments*. PhD Thesis, Delft University of Technology, Delft, the Netherlands.

De Silva, N. (2008). Use of PC elements for waste minimization in the Sri Lankan construction industry. *Structural Survey* ***26****, 188-198.*

Department for Business Innovation and Skills (BIS). (2010). Estimating the Ammount of CO_2Emissions That the Construction Industry Can Influence. *Supporting Material for The Low Carbon Construction IGT Report.http://www.bis.gov.uk.*

Ecoinvent Centre Database (2010). Swiss Centre for Life Cycle Inventories. Retrieved from *http://www.ecoinvent.org/database/*

Economic Planning Unit (2012). Tenth Malaysia Plan 2011-2015, The Economic Planning Unit, Prime Minister's Department. Retrieved from*http://www.epu.gov.my*

Elnimeiri, M. and Almusharaf A. (2010). The Interaction Between Sustainable Structures and Architectural Form of Tall Buildings. *International Journal of Sustainable Building Technology and Urban Development* ***1****, 35–41.*

Environmental Protection Agency, U.S. (2010). Retrieved from *http://www.epa.gov*

Environmental Protection Department, Hong Kong. (2011). Retrieved from *http://www.info.gov.hk/epd*

EPA (2009). *Potential for Reducing Greenhouse Gas Emissions in the Construction Sector*. Washington, DC: Environmental Protection Agency.

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

Fatta, D., Papadopoulus, A., Kourmoussis, F., Mentzis, A., Sgourus, E., Moustakas, K., Loizidou, M. (2003). Estimation methods for the generation of construction and demolition waste in Greece. *'Construction and Demolition Waste' from the International Conferences of Sustainable Waste Management and Recycling*. Editors: Limbachiya, M. and Roberts, J.J. Thomas Telford Publishing, London (2004).

Ferguson, J., Kermode, N., Nash, C.L., Sketch, W.A.J., Huxford, R.P. (1995). *Managing and minimizing construction waste: a practical guide*. Thomas Telford Publications, London.

Franklin Associates (1998). *Characterization of building-related construction and demolition debris in the United States*. The U.S. Environmental Protection Agency Municipal and Industrial Solid Waste Division Office of Solid Waste Report No. EPA530-R-98-010.

Garcìa, N., Irusta, R., Núnez, Y., Moral, A. (2007). Environmental performance of waste based construction materials. LCA study. *In: Peter Claisse, Sadeghi-Pouya, Tarun.R. Naik, Yoon-moon Chun, ed. Proc. Int. Conf: Sustainable construction materials and technologies, 11-13 June 2007 Coventry, Supplementaryproceedings., Pub. UW Milwaukee CBU, pg 28-35*.

Gavilan, R.M., Bernold, L.E. (1994). Source evaluation of solid waste in building construction. *Journal of Construction Engineering & Management* ***120 (3),*** *ASCE Publications.*

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

Green Building Index (GBI) (2010). Retrieved from *http://www.greenbuildingindex.org*

Haron, N.A., Kadir, S., Jaafar, M.S. (2005). Building cost comparison between conventional and formwork system: a case study of four-storey school building in Malaysia. *American Journal of Applied Sciences.*

Haron, N.A., Rahman, H.A., Hanid, M. (2009).Literature review of the advantages and barriers to the implementation of IBS in construction industry. *Malaysian Construction Research Journal* ***4(1)****.*

Hendrickson, C.T., and Horvath, A. (2000), Resource Use and Environmental Emissions of U.S. Construction Sectors. *Journal of Construction Engineering and Management, ASCE,* ***126 (1)****, pp. 38-44.*

Houghton, J.T. (1997). *Global Warming: The Complete Briefing*. Cambridge, UK, Cambridge University Press.

Hsiao, T.Y., Huang, Y.T., Yu, Y.H., Wernick, I.K. (2002). Modeling materials flow of waste concrete from construction and demolition wastes in Taiwan. *Resources Policy **28**, 39-47.*

Humphreys, K., Mahasenan, M., (2002). Towards a Sustainable Cement Industry – Substudy 8: Climate Change. *World Business Council for Sustainable Development: Cement Sustainability Initiative.*

IDEMAT Online LCI Database, Netherlands (2010). Retrieved from *http://www.idemat.nl/*

Industrialized Building System (IBS) Center (2009). Retrieved from *http://www.cidb.gov.my/ibs*

International Organization for Standardization (ISO) 14040. (2006). *Environmental Management-Life Cycle Assessment - Principles and Framework (ISO14040:2006).* Geneve.

Jalali, S (2007). Quantification of Construction Waste Amount. *6th International Technical Conference of Waste, Viseu, Portugal, October 2007.*

Katz, A., Baum, H. (2011). A novel methodology to estimate the evolution of construction waste in construction sites. *Journal of Waste Management **31**, 353 – 358.*

Keys, A., Baldwin, A., Austin, S. (2000). Designing out to encourage waste minimization in construction industry. *In: proceedings of CIBSE, Dublin, September 2000.*

Kibert, C.J. (2002). Deconstruction's Role in an Ecology of Construction. *In: Proceeding of Design for Deconstruction and Materials Reuse (CIB Publication 272).* CIB Task Group 39 – Deconstruction Meeting, Karlsruhe, Germany.

Kim, J.H., Cha, H.S., Shin, D.W. (2006). $LCCO_2$ Assessment for Construction Wastes: The Simplified LCA Study for High Rise Residential Building Project. *In: Proceedings of the International Conference on Sustainable Building Asia, 27-29 June 2007, Seoul, Korea (pg 1217 – 1222).*

Lachimpadi, S.K., Pereira, J.J., Taha, M.R., Mokhtar, M. (2012). Construction waste minimization comparing conventional and precast construction (mixed and IBS) methods in high-rise buildings: A Malaysia case study. *Resources, Conservation and Recycling **68**, 96 – 103.*

Lau, H.H., Whyte, A., Law, P.L. (2008). Composition and characteristics of construction waste generated by residential housing projects. *Int. Journal of Environmental Research, **2(3)**, 261-268.*

Lee, K.M., Inaba, A. (2004). "LCA: Best Practice of ISO 14000 Series". Committee on Trade and Investment of Korea, pp. 1-4.

Li , X., Zhu, Y., Zhang, Z. (2010).An LCA-Based Environmental Impact Assessment Model for Construction Processes. *Building and Environment **45**, 766-767.*

Lim, P. C. (2006). *Implementation strategy for industrialized building system*. M.Sc Thesis, Universiti Teknologi Malaysia.

Llatas, C. (2011). A model for quantifying construction waste in projects according to the European waste list. *Journal of Waste Management* ***31,*** *1261-1276.*

Low, S.P., and Choong, J.C. (2001a). A study of the readiness of precasters for just-in-time construction. *Work Study* ***50(4)****, 131-140.*

Low, S.P., and Choong, J.C. (2001b). Just-in-time management in precast concrete construction: a survey of the readiness of main contractors in Singapore. *Integrated Manufacturing System* ***12(6),*** *416-429.*

Lu, W., Yuan, H., Li, J., Hao, J.J.L., Mi, X., Ding, Z. (2011). An empirical investigation of construction and demolition waste generation rates in Shenzhen city, South China. *Journal of Waste Management* ***31****, 680 – 687.*

Lu, W., and Yuan, H. (2012). Off-site sorting of construction waste: What can we learn from Hong Kong? *Recources, Conservation and Recycling* ***69****, 100 – 108.*

Malaysia Solid Waste & Public Cleansing Management Act No. 672 (2007).

Martinez Lage, I., Martinez Abella, F., Vazquez Herrero, C., Perez Ordonez, J.L. (2009).Estimation of the annual production and composition of C&D debris in Galicia, Spain. *Journal of Waste Management* ***30 (4),*** *636-645.*

Mokhtar, S.N., Mahmood, N.Z. (2008). Approach in construction industry: a study on prefabrication method as a tool for waste minimization. *International Conference of Environment and Research Technology, June 2008, Penang, Malaysia.*

Nitivattananon, V., Borongan, G. (2007). Construction and demolition waste management: current practices in Asia. *International Conference on Sustainable Waste Management, September 2007, 97-104.*

Nunnally, S.W. (2007). *Construction methods and management.* New Jersey: Pearson Prentice-Hall.

Ofori, G., Ekanayake, L.L. (2000a). Building waste assessment score: design-based tool. *Building and Environment* ***39****, 851-861.*

Ofori, G., Ekanayake, L.L. (2000b). Construction material waste source evaluation. *Proceedings: Strategies for a Sustainable Built Environment, Pretoria.*

Ong, E. G. (2009).*Construction waste generated in conventional method of housing construction*. M.Sc Thesis, Universiti Teknologi Malaysia.

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

Osmani, M. (2012). Construction waste minimization in the UK: Current pressures for change and approaches. *Procedia – Social and Behavioral Sciences* ***40****, 37 – 40.*

Petersen A.K.,Solberg B. (2005). Environmental and Economic Impacts of Substitution Between Wood Products and Alternative Materials: A Review of Micro-Level Analyses From Norway and Sweden. *Forest Policy and Economics* ***7****, 249-259.*

Poon, C.S., Jaillon, L. (2002). *A guide for minimizing construction and demolition waste at the design stage*. Hong Kong: Hong Kong Polytechnic University Publishing.

Poon, C.S., Jaillon, L. (2004). Reducing building waste at construction sites in Hong Kong. *Construction Management and Economics (22).*

Poon, C.S., Yu, A.T.W., Wong, S.W., Cheung, E. (2004). Management of construction waste in public housing projects in Hong Kong. *Construction Management and Economics **(22),** 675-689.*

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

Poon, C.S., Jaillon, L. (2009b). The evolution of prefabricated residential building system in Hong Kong: A review of public and private sector. *Automation in Construction **18**, 239-248*.

Poon, C.S., Yip, R. (2005). Comparison of the use of traditional and low waste formwork system in Hong Kong. *World Sustainable Building Conference, 2005.*

Poon, C.S., Yu, A.T.W., Ng, L.H. (2001a). On-site sorting of C&D waste in Hong Kong.*Resources, Conservation and Recycling **32**, 157-172.*

Poon, C.S., Yu, T.W., Ng, L.H. (2001b). *A guide for managing and minimizing building and demolition waste*. Hong Kong: Hong Kong Polytechnic University Publishing.

Poon, C.S., Yu, A.T.W., Ng, L.H. (2003). Comparison of low-waste building technologies adopted in public and private housing projects in Hong Kong. *Engineering, Construction, and Architectural Management **10**, 88-98*.

Rodriguez, G.; Alegre, F.J.; Martinez, G. (2007). The contribution of environmental management systems to the management of construction and demolition waste: The case of the Autonomous Community of Madrid (Spain). *Resources Conservations & Recycling **50**, 334-349.*

Säynäjoki, A., Heinonen, J.,Junnila, S. (2011). Carbon Footprint Assessment of a Residential Development Project.*International Journal of Enviromental Science and Development, **2(2)**.*

Shin, S., Tae, S., Woo, J., Roh, S. (2011). The Development of Environmental Load Evaluation System of A Standard Korean Apartment House. *Renewable and Sustainable Energy Reviews **15**, 1239–1249.*

Skoyles, E.R. and Skoyles, J.R. (1987). *Waste Prevention on Site.* Mitchell Publishing, London.

SMARTWaste, UK (2009). Retrieved from *http://www.smartwaste.co.uk*

Solis-Guzman, J., Marrero, M., Montes-Delgado, M.V., Ramirez-de-Arellano, A. (2009). A Spanish model for quantification of construction waste. *Journal of Waste Management, **29 (9)**, 2542 – 2548*.

Tae S., Baek, C.,Shin S. (2010). Life Cycle CO_2 Evaluation on Reinforced Concrete Structures with High-Strength Concrete. *Environmental Impact Assessment Review, doi:10.1016/j.eiar.2010.07.002.*

Tam, C.M., Deng, ZM., Zeng, S.X. (2002). Evaluation of construction methods and performance for high rise public housing construction in Hong Kong. *Building and Environment **37**, 983-991*.

Tam, V.W.Y., Tam, C.M., Ng, W.C.Y. (2007a). On prefabrication implementation for different project types and procurement methods in Hong Kong. *Journal of Engineering, Design, and Technology **5**, 68-80.*

Tam, V.W.Y., Tam, C.M., Zeng, S.X., Ng, W.C.Y. (2007b). Towards adoption of prefabrication in construction. *Building and Environment **42**, 3642-3654*.

Tam, V.W.Y., Shen, L.Y., Fung, I.W.H., Wang, J.Y. (2007c). Controlling construction waste by implementing governmental ordinance in Hong Kong. *Construction Innovation **7(2),** 149-166.*

Tam, V.W.Y, Wang, J.Y., Kang, X.P. (2008). An investigation of construction waste: an empirical study in Shenzhen. *Journal of Engineering Design and Technology **6(3).***

Tam, V.W.Y. (2008). On the effectiveness in implementing a waste-management-plan method in construction. *Journal of Waste Management **28**, 1072-1080.*

Tam, V.W.Y., Shen, L.Y., Li, C.Y. (2009). Benefit analysis on replacing in situ concreting with precast slabs for temporary construction works in pursuing sustainable construction practice. *Resources, Conservation and Recycling **53**, 145-148.*

Thanoon, W.A.M., Lee, W.P., Kadir, M.R.A., Jaafar, M.S., Salit, M.S. (2003). The essential characteristics of industrialized building system. *International Conference on Industrialized Building Systems, Kuala Lumpur, pp 283-294.*

Trusty, W. B., Meil, J. K. (2002). Building Life Cycle Assessment: Residential Case Study. *Proceedings: Mainstreaming Green: Sustainable Design for Buildings and Communities. Chattanooga, TN.*

Urio, A.F., Brent, A.C. (2006). Solid waste management in Botswana: reduction of construction waste. *Journal of South African Institute of Civil Engineering **48(2),** 18-22.*

Vogtlander, J.G., Brezet, H.C., Hendriks, C.F. (2001). The Virtual Eco-Costs '99 – A Single LCA-Based Indicator for Sustainability and the Eco-Costs-Value Ratio. A New LCA-Based Calculation Model to Determine the Sustainability of Products and Services. *International Journal of Life Cycle Assessment, **6 (3),** 157-166*.

Vogtlander, J.G., Hendriks, C.F. (2002). "The Eco-costs/Value Ratio (EVR) – Material and Ecological Engineering". *Aeneas Technical Publisher, Boxtel*.

Vogtlander, J.G., Hendriks, C.F., Janssen, G.M.T. (2006). The Eco-Costs/Value Ratio, A Tool To Determine The Long Term Strategy Of De-Linking Economy And Environmental Ecology. *International Journal of Ecodynamics, **1(2)**, 136-148*.

Wiedmann, T., Minx, J. (2008). A Definition of 'Carbon Footprint' *In: C. C. Pertsova, Ecological Economics Research Trends: Chapter 1, pp. 1-11, Nova Science Publishers, Hauppauge NY, USA.*

Yahya, K., Boussabaine, A.H. (2006). Eco-costing of Construction Waste. *Management of Environmental Quality: An International Journal **17 (1),** 6 – 19.*

Yahya, K. and Boussabaine, A.H. (2010). Quantifying Environmental Impacts and Eco-Costs From Brick Waste. *Architectural Engineering and Design Management **6**, 189-206.*

Yau, R., Cheng, V., Kam, G. (2007). Developing Life Cycle Assessment Tool for Buildings in Hong Kong. *The 6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings IAQVEC 2007, Sendai, Japan.*

Yuan, H., Chini, A.R., Lu, Y., Shen, L. (2012). A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste. *Waste Management **32**, 521 – 531*.

Zabalza-Bribián, I., Valero-Capilla, A., Aranda-Usón, A. (2011). Life Cycle Assessment of Building Materials: Comparative Analysis of Energy and Environmental Impacts and Evaluation of The Eco-efficiency Improvement Potential. *Building and Environment **46**, 1133-1140*.

Zhang, X., Wu, Y., Shen, L. (2012). Application of low waste technologies for design and construction: A case study in Hong Kong. *Renewable and Sustainable Energy Reviews **16**, 2973 – 2979.*